TECHNOLOGY QUARTERLY

AND

PROCEEDINGS OF THE SOCIETY OF ARTS.

VOL. XVII MARCH, 1904 NO. 1

PROCEEDINGS OF THE SOCIETY OF ARTS.

FORTY-SECOND YEAR, 1903–1904.

BOSTON, October 15, 1903.

THE 583d regular meeting of the SOCIETY OF ARTS was held in Room 6, Lowell Building, on Thursday evening, October 15, at eight o'clock, Professor Swain in the chair. Two hundred and fifty persons were present.

After the minutes of the previous meeting had been read and approved, Mr. J. Edwin Jones was elected to Associate Membership in the Society.

Mr. John P. Fox then addressed the Society on "American Rapid Transit in the Light of European Experience." The lecture was fully illustrated with lantern slides. A vote of thanks was tendered the speaker, and the meeting adjourned.

BOSTON, October 29, 1903.

The 584th regular meeting of the SOCIETY OF ARTS was held in Room 22, Walker Building, on Thursday evening, October 29, at eight o'clock, Mr. Blodgett in the chair. Ninety persons were present.

After the minutes of the previous meeting had been read and approved, Major A. W. Lowe was elected to Associate Membership in the Society.

Captain William H. Jaques then addressed the Society on "Solar Evaporations: Their Development and Use in Water Engineering."

A vote of thanks was tendered the speaker, and the meeting adjourned.

BOSTON, November 12, 1903.

The 585th regular meeting of the SOCIETY OF ARTS was held in Room 22, Walker Building, on Thursday evening, November 12, at eight o'clock, Mr. James P. Munroe in the chair. One hundred and fifteen persons were present.

After the reading of the minutes of the previous meeting, Mr. William Lyman Underwood addressed the Society on "Mosquitoes and Suggestions for Their Extermination."

The speaker gave a clear account of the complete life-history of various common species of mosquitoes, and described a number of methods for their extermination which had been used with success. The lecture was fully illustrated with specimens and with lantern slides made from life.

A vote of thanks was tendered the speaker, and the meeting adjourned.

BOSTON, November 30, 1903.

The 586th regular meeting of the SOCIETY OF ARTS was held in Room 6, Lowell Building, on Wednesday evening, November 30, at eight o'clock, President Pritchett in the chair. Two hundred and fifty persons were present.

After the minutes of the previous meeting had been read and approved, Professor Simon Newcomb addressed the Society on "One Field of Twentieth Century Science."

A vote of thanks was tendered the speaker, and the meeting adjourned.

BOSTON, December 10, 1903.

The 587th regular meeting of the SOCIETY OF ARTS was held in Room 22, Walker Building, on Thursday evening, December 10, President Pritchett in the chair. Two hundred and fifty persons were present.

After the minutes of the previous meeting had been read and approved, Mr. Donald M. Belcher was elected to Associate Membership in the Society.

Dr. Herbert W. Wiley then addressed the Society on "The Influence of Food Preservatives on Digestion."

A vote of thanks was tendered the speaker, and the meeting adjourned.

BOSTON, December 31, 1903.

The 588th regular meeting of the SOCIETY OF ARTS was held in Room 22, Walker Building, on Thursday evening, December 31, at eight o'clock, Professor Lanza in the chair. Two hundred and fifty persons were present.

After the minutes of the previous meeting had been read and approved, Mr. Charles P. Moat was elected to Associate Membership in the Society.

Mr. Charles Garrison, of the De Laval Steam Turbine Company, then addressed the Society on "Steam Turbines." A number of specimens were exhibited. The lecture will be published in the TECHNOLOGY QUARTERLY.[1]

After a discussion of the paper by members of the Society and others, a vote of thanks was tendered the speaker, and the meeting adjourned.

JAMES F. NORRIS, *Secretary.*

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[1] Below, pp. 4–21.

THE DE LAVAL STEAM TURBINE.

By CHARLES GARRISON, S.B.

(Read December 31, 1903.)

I WILL not touch upon the historical side of the turbine, as you will find this amply done by many authors, notably in a paper by Professor Thurston,[1] and also in an excellent book by R. W. Neilson.[2] In this book you will find the development of the steam turbine from earliest inventions to the commercial forms of De Laval, Parsons, and Curtis. Other types claiming some notice abroad are given; for example, the Rateau and the Seger.

Today three types of steam turbines are recognized. The first type is the De Laval (Figure 1), using a single wheel at high velocity, expanding the steam completely in the nozzles before reaching the wheel, and therefore having none of the working parts under pressure. The second type is the Parsons, which has a large number of wheels. Between each wheel, opposite the buckets, is an annular ring of vanes to deflect the steam from one wheel to the next. The steam, therefore, passes through a sinuous path, thereby allowing the wheels, which are fixed to one shaft, to rotate at a much lower speed than the first type. The Curtis forms the third type, and is intermediate between these two, having first a set of expanding nozzles, then a small series of wheels, then a second set of nozzles with its series of wheels. The Parsons turbine is manufactured by the Westinghouse Machine Company, and the Curtis turbine by the General Electric Company.

We will now consider the principal parts of the De Laval steam turbine (Figure 2). The first to be noted is the wheel with the buckets fixed in its periphery. This is placed on the shaft which carries a double-cut spiral pinion at the other end. This long, flexible shaft is a very essential part of the turbine. The bearings for the wheel are of the ball and socket type, so that the shaft may have some

[1] *Transactions of the American Society Mechanical Engineers*, December, 1900.

[2] "The Steam Turbine." Longmans, Green & Co., second edition, 1903.

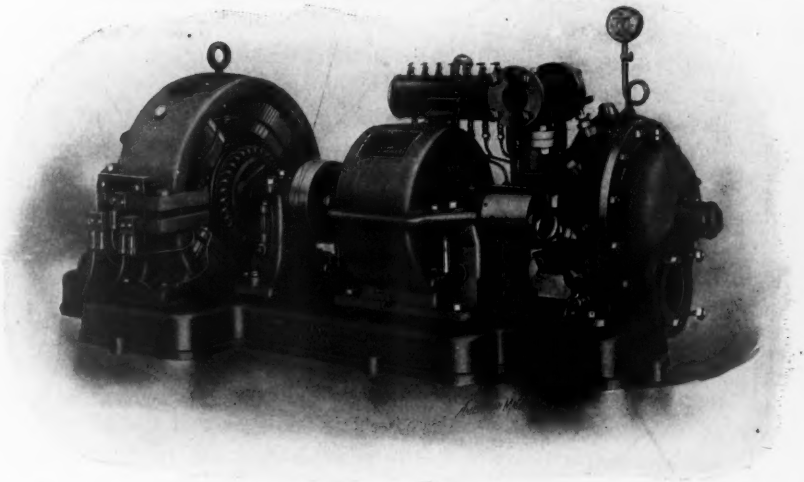

FIG. 1.—DE LAVAL STEAM TURBINE DYNAMO. 30 H. P., 20 K. W., DIRECT CURRENT.

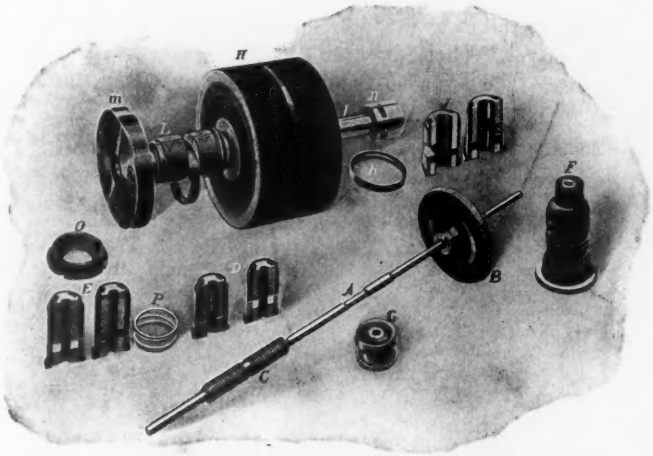

FIG. 2.—WORKING PARTS OF THE DE LAVAL STEAM TURBINE.

A. Turbine shaft; *B.* Turbine wheel; *C.* Pinion; *D.* Pinion bearing, two parts; *E.* Pinion bearing, two parts; *F.* Wheel bearing with spring; *G.* Flexible bearing; *H.* Gear-wheel; *I.* Gear-wheel shaft; *J.* Gear-wheel bearing, two parts; *K.* Oil ring; *L.* Gear-wheel bearing in position; *M.* Coupling; *N.* Centrifugal governor; *O.* Gland adjusting nut; *P.* Adjusting nut for flexible bearing.

slight movement. With wheels moving at such high velocities as these, the rates being from 10,000 to 30,000 revolutions per minute, it would be nearly impossible to secure perfect balance so that the centre of gravity would coincide with the centre of figure. Therefore the shaft is allowed to take a slight flexture in order that the wheel and shaft may revolve about the centre of gravity of these combined parts. That is, while the wheel is in motion the flexture is permanent and the wheel has a slight eccentric motion, seldom more than a few thousandths of an inch. You will observe that the shaft does not bend back and forth with each revolution. These high-speed parts are made of forged nickel steel, which has great tensile strength.

Second in importance are the gears, which mesh with the pinion and reduce the speed to one-tenth that of the turbine wheel. These are of the double-cut spiral type for smooth and quiet running. Turbines of 55 horse power and smaller have but one gear, and those that are 75 horse power and over have two gears, so that the pressure on the pinion and its bearings may be approximately equal from each side.

The third principal part consists of the set of nozzles distributed around the wheel, the number of nozzles depending upon the size of the turbine and the steam conditions. These play a most important part in the operation of the turbine, and we will now take up their action in detail. Their relation to the wheel is clearly shown in Figures 3 and 4, as is also the hand valve by which each nozzle is controlled.

All turbines operate by virtue of the kinetic energy of the steam, and in this respect are similar in action to water wheels of the Pelton type. The economy of the turbine surpasses that of the steam engine in three points: first, the entire static energy of the steam is transferred into kinetic energy; second, part of the steam under adiabatic expansion in a nozzle is condensed and gives up its latent heat to increase its speed; and third, the friction of the turbine is nearly constant for all loads.

The steam enters the nozzles at the initial pressure with its corresponding temperature (or higher if superheat be used) and at a very small velocity. By the time the steam has reached the larger end of the nozzle it has acquired an enormous velocity, due to its adiabatic expansion, while the pressure and temperature have fallen to very nearly that of the atmosphere or condenser (if running condensing). Its elastic properties are now of no further use, and to all intents

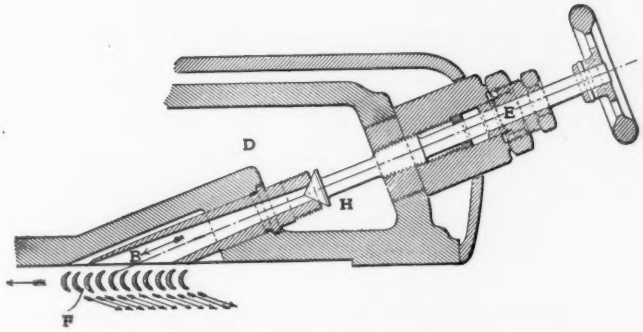

FIG. 3.—THE DE LAVAL NOZZLE.

D. Steam chamber; *E.* Valve stem; *H.* Valve; *B.* Point of discharge; *F.* Buckets.

and purposes it is merely a mass of rapidly moving particles. These particles enter the turbine buckets and give up their kinetic energy to rotate the wheel. Thus in less than a ten thousandth of a second the steam gains a tremendous velocity and loses it again.

You will note that the expansion is adiabatic, since every element of the nozzle assumes a temperature that is constant and is equal to that of the passing steam; likewise the volume of steam entering at maximum pressure gradually expands to its minimum pressure at the outlet,

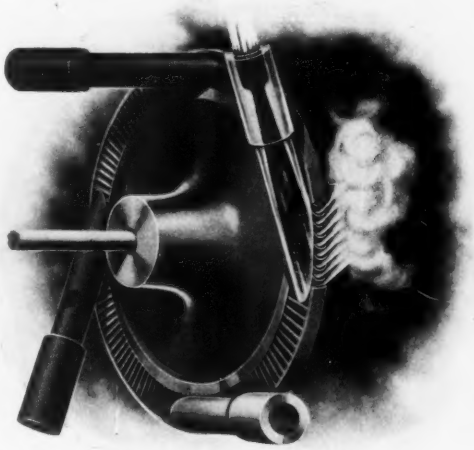

FIG. 4.—THE DE LAVAL TURBINE WHEEL AND NOZZLES.

this being the same as that of the surrounding medium. No loss in conversion has, therefore, occurred, all the energy being given to accelerate the particle of steam. The steam at the point of discharge issues in a solid jet without the tendency of its particles to diverge in any direction.

I now wish especially to dwell on the design of the nozzle and the action of the steam under differing conditions in the same nozzle, as this brings up an interesting and important question. With a certain initial and final pressure, in order to get the maximum velocity of the steam at the periphery of the wheel, the divergence of the nozzle must be definitely and accurately determined. We will take a case where the initial pressure is 150 pounds (by gauge) and a vacuum of 26 inches of mercury, represented by about 1.9 pounds pressure absolute. Under these conditions the speed of the steam will be 3,800 feet per second. Now, suppose we vary the terminal pressure to 20 inches vacuum or about 4.9 pounds pressure absolute, using the same nozzle. You will at once see that the point where 4.9 pounds pressure occurs is well within the nozzle, and that full expansion has been completed at that point. The steam then has to travel a certain distance along a diverging path, and therefore its speed is diminished appreciably by the time it reaches the periphery of the wheel; and, as the energy delivered to the wheel is proportionate to the square of the velocity of the steam, the power drops off very rapidly.

Suppose we change our initial pressure from 150 to 100 pounds (by gauge), leaving the final pressure 26 inches, or 1.9 pounds absolute, as in the first case, while using the same nozzle, what will be the effect in cutting down the power? It will be very small, and could be compensated for by opening an additional nozzle so as to give a greater steam admission area.

The reason why the terminal pressure makes such a vast difference and the initial pressure such a small difference is clearly shown if we represent the volumes dealt with under the differing conditions. At 150 pounds gauge pressure the volume of the steam is 2.75, and at 1.9 pounds pressure absolute, or 26 inches, the volume is 190, so that the admission area of the nozzle must allow 2.75 volumes to pass at a very low speed, while at the discharge end 190 volumes must pass at a very high rate of speed.

Now if the vacuum be but 20 inches, or 4.9 pounds absolute, the corresponding volume is 75, so that the point where this volume passes

is well up in the nozzle, and there is a constant loss of speed the rest of its journey, its elastic property having ceased at that point.

With the lower steam pressure (100 pounds gauge) and the same vacuum (26 inches), the volume at admission is changed from 2.75 to 3.86, while the volume on discharge is still 190, so that the difference in initial volume is but a small part of the total volume on emission.

To show the actual loss of power due to the changed conditions:

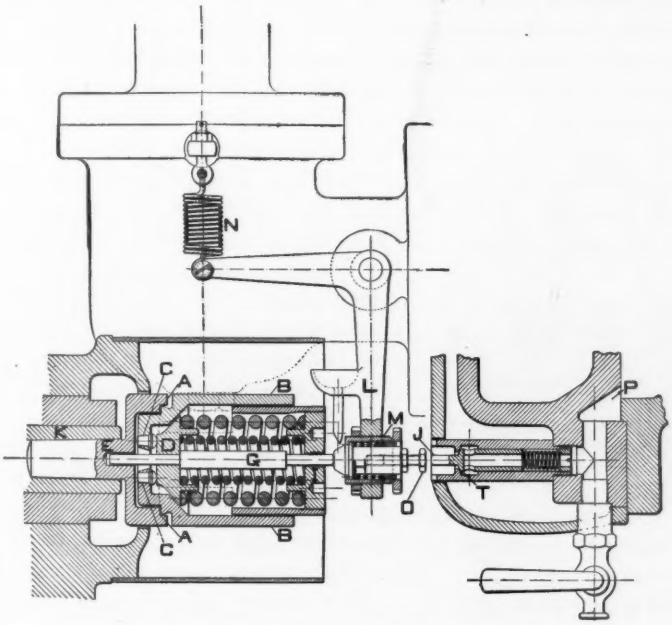

FIG. 5.—DE LAVAL GOVERNOR AND VACUUM VALVE.

the velocity under the first case where the nozzle was suited to the conditions equals 3,800 feet per second. The velocity under the second case, with 20 inches vacuum, equals about 2,800 feet per second, so that the power delivered to the wheel fell as $\frac{2,800^2}{3,800^2}$, or nearly one-half, while with the change of steam pressure from 150 to 100 pounds (gauge) the loss in power is 8 per cent., due to the admission area being too small for sufficient steam to pass through the nozzle at this lower pressure. The turbines are designed so that the combined nozzle area will allow

a 10 per cent. continuous overload, and this also will care for 25 per cent. momentary overloads without decreasing the speed of the wheel more than a slight amount.

The fourth part is the governor (Figures 5 and 6), which is very cleverly and simply made; it is of the throttling type. This governing device is placed on the end of the gear shaft, and a throw of the plunger of .14 of an inch shuts off the steam completely. When run condensing, an additional attachment is used whereby if the governor fails to act for any reason the plunger pushes a valve inward and admits air to the vacuum chamber in which the wheel revolves. This immediately puts an air brake on the wheel and prevents an acceleration of speed, although the throttle valve be wide open. This little safety device is of great importance, and its value is well shown by the following illustration.

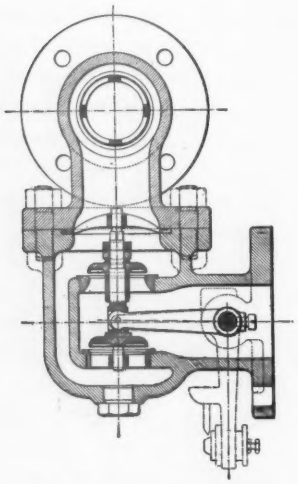

FIG. 6.—GOVERNOR VALVE.

Suppose through any cause the speed tends to become excessive, air is admitted to the wheel chamber, and the vacuum reduced from say 26 inches to 10 inches, or lower, immediately the velocity of the steam is greatly diminished, as was shown when comparing the same nozzle with different terminal pressures. By this device the speed of the wheel will be cut down below its normal, even though there is no load on the turbine and the throttle is wide open.

To show this action more clearly I started a 150-horse power turbine with all nozzles open, the nozzles being designed for 150 pounds gauge pressure and 26 inches vacuum; the condenser was shut down and the turbine exhausted against the atmosphere, and with these conditions the turbine would not come up to full speed with no load.

Now it can be shown readily that the maximum efficiency of the turbine is obtained when the peripheral velocity is about one-half the speed of the steam, and it is this condition we wish to approach; but we do not reach it, however, on account of the great centrifugal forces set up by such high velocities. To illustrate vividly the stress

upon the wheel: should a cubic inch of iron (weighing about $\frac{1}{4}$ pound) be placed on the periphery of certain De Laval turbine wheels running at their normal speeds, it would require the pull of a strong locomotive to hold it in place.[1]

An average speed for the steam may be taken as 4,000 feet per second, and if the maximum efficiency occurs when the peripheral velocity is 47 per cent. of the steam velocity, this would give a peripheral speed of 1,880 feet per second; but as the highest speed we now use is about 1,350 feet per second, this would make the efficiency about 94 per cent. of the theoretical value.

Another source of loss is caused by being obliged to deliver the steam upon the wheel at an angle of 20 degrees. This loss amounts to about 6 per cent., leaving a net efficiency of 88 per cent. Some slight loss occurs, due to the gears and bearings, but probably the greatest of all is from fluid and air friction. This has not yet been even approximately determined, so far as I know; it is simply estimated as a residual loss.

The advantages presented by the turbine over the reciprocating engine are many, and the principal ones are as follows:

1. Advantages in construction.
2. Advantages in economy.

The first point of advantage in construction is its simplicity and the small number of working parts — always a desideratum — there being but the wheel with its one or two gears (as the case may be) in motion. The high speed allows bearings of small diameters, such as $\frac{7}{8}$ inch for the 150 horse power and $1\frac{1}{8}$ inches for the 300 horse power. It is but the labor of a short time to take the working parts out, and the replacement of any bearing can be done in ten minutes without raising a single working part. There are no bearings to adjust or parts to be taken up on account of wear (Figure 7).

The second point is the close speed regulation. This is due to the simple governing mechanism, rendered sensitive by the high speed at which the geared shaft revolves, and also to the constant angular velocity, which the steam engine nowise approaches when dealing with variable loads. The evenness of rotation is of much value where alternating current machines are run in parallel.

For the regulation at different loads a test made by Dean and Main

[1] This illustration is taken from a paper by R. M. Neilson.

shows a maximum speed variation of $\frac{8}{10}$ of 1 per cent. For sudden heavy overloads the momentary variation is, of course, somewhat greater.

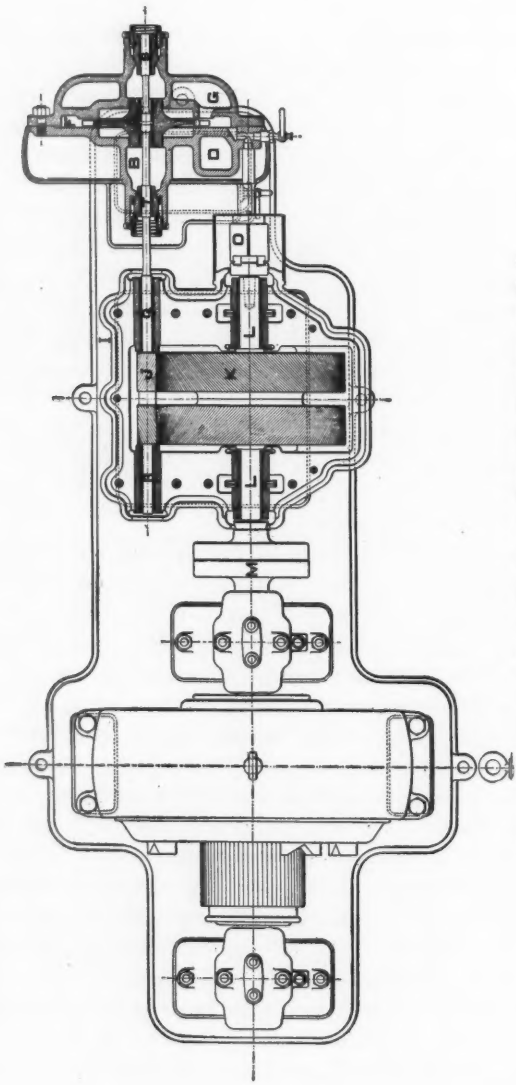

FIG. 7.—SECTIONAL PLAN DE LAVAL TURBINE DYNAMO, 30 H. P.

The third point is the perfect balance and absence of vibration. This is due to the flexible shaft, allowing the wheel to rotate about its centre of gravity, so that no vibration is transmitted by the surrounding floors or piping. Compare this with the reciprocating engine, which transmits its thrust to the building, or its vibration the entire height of the structure, owing to its intermittent exhaust.

The fourth point is that no moving parts are under pressure, which simplifies the wheel and bearings and allows light construction. Also, since the steam is completely expanded before reaching the wheel, the turbine is not limited to any initial steam pressure, but can work as readily at 1,000 pounds pressure as at 100 pounds. The gain by the use of high pressures is well shown by the curves (Figures 8 and 9), which are taken from actual tests.

The fifth point is the small space occupied. This is clearly an advantage in city installations or on board ship, where floor space is valuable, and it allows several units to be arranged to great advantage and cared for with greater ease.

The sixth point is the smallness of the foundations necessary and the ease of erection. Since there is no thrust no other foundation is necessary than that which will hold the dead weight rigidly, and this often makes a great saving in expense. The units, being comparatively light and small, are shipped completely assembled, and can be moved into place quickly and connected to the piping with great facility.

The seventh point is the automatic oiling and the small amount of oil necessary. The reduced speed bearings are all of the ring oil type, while a reservoir on the turbine gear case, or upon the wall, feeds the high speed bearings (four in number) and supplies the drips upon the gear wheels. The gear-wheel compartments are large, and the oil after being used falls to this point, where it is drawn off, filtered, and used over and over again. The net amount used is, therefore, small. The lubricant should be a pure mineral oil, like that used for spindles and similar work, and the best grade is worth about twenty cents per gallon. This same oil is used throughout all the bearings. An important feature in connection with the oil is that the steam is not in contact with it, and the exhaust can be returned to the boilers without being purified.[1]

The eighth point is freedom of danger from water. Water in the

[1] A few cases have been noticed where traces of oil were carried over when the turbine was under high vacuum.

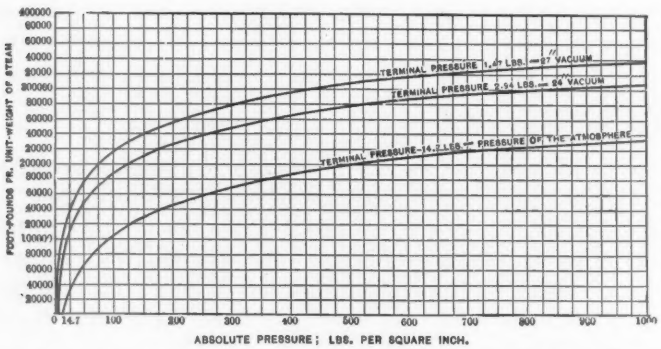
FOOT-POUNDS PR. UNIT-WEIGHT OF STEAM
TERMINAL PRESSURE 1.47 LBS. — 27" VACUUM
TERMINAL PRESSURE 2.94 LBS. — 24" VACUUM
TERMINAL PRESSURE 14.7 LBS. — PRESSURE OF THE ATMOSPHERE
0 14.7 100 200 300 400 500 600 700 800 900 1000
ABSOLUTE PRESSURE; LBS. PER SQUARE INCH.

FIG. 8.—ENERGY OF A JET OF STEAM AT VARIOUS INITIAL AND TERMINAL PRESSURES.

steam does not endanger the turbine in any way; it merely slows down the wheel and decreases the efficiency. A good case in point is that of a 30-horse power turbine generator which I recently installed near New York City. The boiler tender left the pump running until the boiler was full of water and the turbine was working like a Pelton water wheel. No damage was done, however, the turbine merely slowing down, and as soon as the steam was free from water the turbine resumed its normal jovial pace. It is unnecessary to ask how long a piston engine would have lasted under the same treatment.

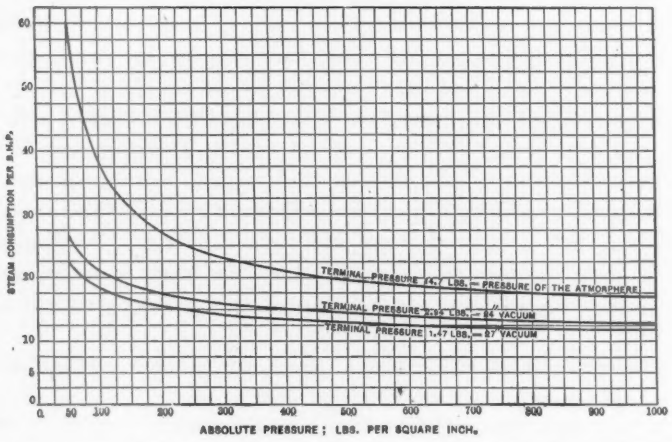
STEAM CONSUMPTION PER B.H.P.
TERMINAL PRESSURE 14.7 LBS. — PRESSURE OF THE ATMOSPHERE
TERMINAL PRESSURE 2.94 LBS. — 24" VACUUM
TERMINAL PRESSURE 1.47 LBS. — 27" VACUUM
0 50 100 200 300 400 500 600 700 800 900 1000
ABSOLUTE PRESSURE; LBS. PER SQUARE INCH.

FIG. 9.—ACTUAL STEAM CONSUMPTION PR. B. H. P. DE LAVAL STEAM TURBINE.

The last item under this head is the life of this high speed machine. Can it keep up the pace for the long period expected of a prime mover? It has had a test of ten years' active service, and has clearly shown that it has lasting powers. The reason for this is that while the velocities are very high the pressures are very light. Take the gears, for instance, that have from twenty to sixty teeth in mesh, and you will find the pressure per tooth to be from 15 to 50 pounds.

The second head, that of economy of operation, covers some four points, the first being high efficiency with variable and light loads (Figure 10). This is undoubtedly due to the fact that the total fric-

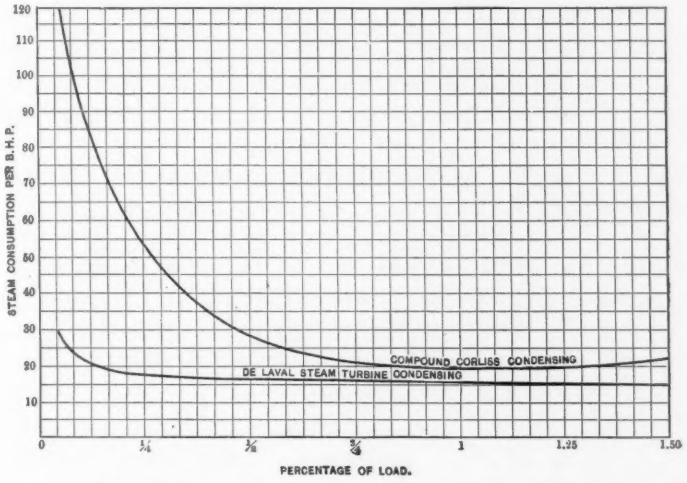

FIG. 10.—COMPARISON OF EFFICIENCY AT VARIOUS LOADS.

tion is constant throughout the whole working range of the turbine, and this is very clearly shown in the test made by Dean and Main with saturated steam.

At 86 per cent. load the increased steam consumption was 2.6 per cent. over full load.

At 59 per cent. load the increased steam consumption was 9.0 per cent. over full load.

At 36 per cent. load the increased steam consumption was 8.1 per cent. over full load.

This economical operation is especially adapted to electrical work where the units are often run for long periods on light loads.

In the second place there is no leakage due to wear. With the reciprocating engine the sources of steam leakage are many, and if not carefully closed lead to considerable loss in efficiency. With the De Laval turbine there are no parts subject to wear which will increase the steam consumption, since none of the working parts are under pressure, and the steam being fully expanded there is no tendency to divert the course of the stream of particles from its straight path. There is a definite clearance between the nozzles and the buckets of the wheel of about $\frac{1}{8}$ inch, and this, of course, remains constant. This turbine has no packing nor stuffing boxes, so that these sources of loss, which occur in other types of engines, are here eliminated.

In the third place there is small friction loss, that is, the friction of the bearings is very slight, owing to the light weight of the moving parts and to the small diameters of the bearing parts. While a 150-horse power turbine wheel rotates at 12,000 revolutions per minute, the shaft bearing is but $\frac{7}{8}$ inch in diameter, and the 300-horse power wheel has a speed of 10,000 revolutions per minute, and has a $1\frac{1}{8}$-inch shaft, as already shown.

Fourth, we have ease of attendance. The point of importance in the care of the turbine is to see that the oil system is feeding freely, for the babbit bearings would soon melt should they run dry. With the compound engine there is a multiplicity of parts which need care and a great number of oil cups to keep filled. Many turbines can easily be cared for by one man where many men would be needed were piston engines used. It is important, however, that a good, reliable man be placed in charge, since any fine machinery needs the most intelligent care.

There now remain three points to be considered, viz., the use of superheat, back pressure, and high vacuum.

Superheat. — The use of superheat is of great advantage to both engine and turbine, but the reason is not altogether the same. In the engine the gain is in freeing the steam from the initial condensation which comes at admission, where it comes in contact with the cold surfaces which have been reduced to the temperature of the exhaust steam. In the turbine there is no equivalent to this form of loss, but one of nearly equal magnitude seems to be the friction of the fluid on the buckets, and also that due to the resisting medium in which the wheel revolves. Superheated steam seems to reduce the fluid frictional loss to a considerable degree by allowing fewer particles of water to come in contact with the revolving parts.

Under adiabatic expansion in a diverging nozzle, the steam, while starting on its journey in a saturated condition, condenses as expansion proceeds, so that under such conditions, as, for example, 150 pounds boiler pressure and 28 inches of vacuum, 23 per cent. of the steam is emitted in the form of water. This part of the steam has, therefore, given up its inner *latent heat* in useful work, that of increasing the velocity of the particle, and it is by using these heat units to advantage that the turbine starts with a higher thermal efficiency than the steam engine.

Mr. Parsons considers that in his turbine 131° F. of superheat reduces the steam consumption about 12 per cent. In estimating the saving expected by the use of superheat with the De Laval turbines, we allow 8 per cent. for 100° F. and 13 per cent. for 200° F. It is probable that the increase in economy is largely due to the reduction of friction, as the percentage is greater than would be due to thermodynamic causes.

A very high degree of superheat can be used by the turbine, as no working parts are affected; while in the engine the problem due to the need of lubrication and to the expansion of the cylinder and piston is a serious one.

It would be interesting to find at just what degree of superheat the highest commercial economy occurs, but we can place the upper theoretical limit not far from 1,470° F., as with steam of 150 pounds pressure this means a temperature of over 1,800° F., which is near the point of dissociation of the steam.

Superheat of about 600° F.,[1] with 150 pounds gauge pressure and a 28-inch vacuum, would give saturated steam at the buckets of the wheel, so that while we gained by diminution of fluid friction, we would lose from lack of condensation and from not freeing the latent heat units.

Back Pressure. — The action of back pressure on the engine and turbine is similar, in the one case reducing the mean effective pressure by the amount of the back pressure, and in the other by making a denser medium in which the turbine wheel revolves. There is no mechanical difficulty in either case, and the exhaust steam can be used for heating purposes.

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[1] Based on the supposition that the specific heat of superheated steam under these conditions would be .80°. It is now known that this is not a constant (usually given as .48°), but rises with pressure and temperature.

High Vacuum. — As back pressure causes a denser medium for the turbine wheel to revolve in, so a high vacuum reduces this frictional element to a minimum, and the gain that this makes is shown in the following examples.

With a 300-horse power wheel operating with 150 pounds gauge pressure, the gain from a vacuum of 22 inches to one of 28 inches is about 6 per cent. per inch, the percentages being figured from the next lower vacuum. A good vacuum, therefore, is much needed where high economy is desired; but the condenser problem is one that needs special consideration, as it takes large cooling surfaces and a great volume of water to produce the usual vacuum of 28 inches of mercury.

A De Laval 300-horse power turbine is now in operation in Dakota, with a vacuum equivalent to 29 inches, using an Alberger condenser, and the steam is delivered with 225° of superheat.

We now come to the different uses to which the De Laval steam turbine is put. Its high speed allows of its efficient use in several fields where the reciprocating engine cannot compete. Perhaps the best known use is with the De Laval cream separator. The turbine wheels used with these simply have the edges upon which the steam strikes notched, the number of revolutions being from 6,000 to 10,000 per minute.

Of the types for power purposes may be mentioned: first, the turbine motor carrying a pulley (or pulleys) for belted work. Second, the direct connected generating sets, with either direct or alternating dynamos. Sizes 50 kilowatts and above have double armatures (Figure 11), thereby giving the two voltages necessary to a three-wire system. This is the most popular use to which the turbine is put at present. The smallest size, 1 kilowatt, is made for locomotive headlights, the set being placed in the cab and taking a space 20 inches long, 10 inches wide, and 10 inches high. This gives current to an enclosed arc lamp. The diameter of this turbine wheel is less than 3 inches, and revolves 39,000 turns per minute.

The De Laval turbine is now applied to train lighting with most satisfactory results. The Pullman Company have a 20-kilowatt for lighting one of their trains between Chicago and New York. The plant is placed in the forward part of the baggage car, and takes its steam from the locomotive. As there are three shifts of engines, each furnishing a different pressure, the turbine is equipped with three sets of nozzles, so that all that is necessary to do to meet the new conditions is to turn off two hand wheels and turn on two others.

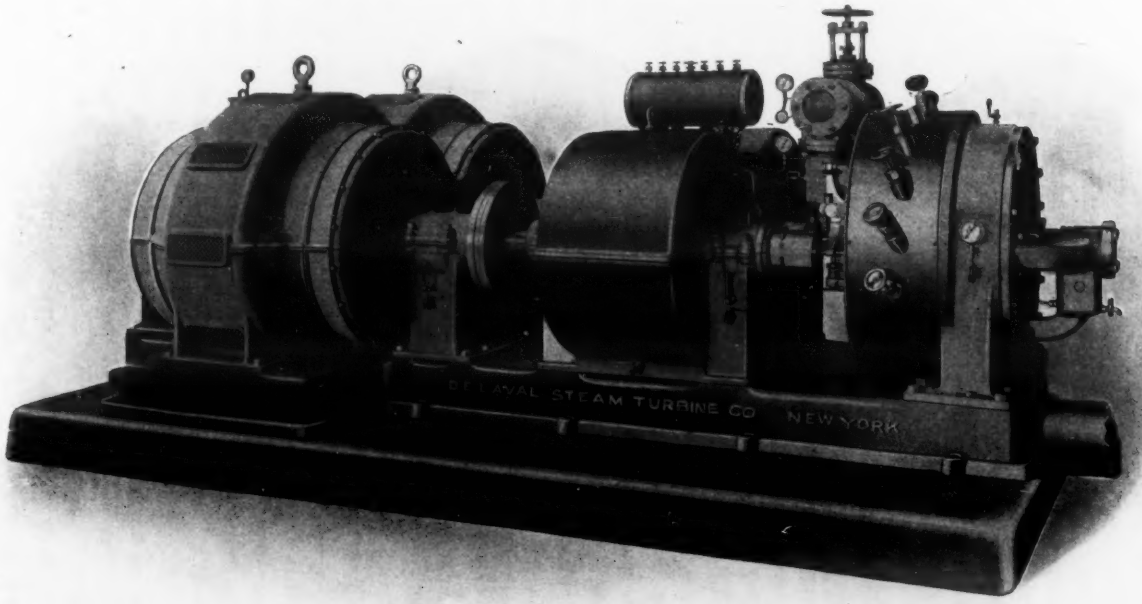

FIG. 11.—DE LAVAL STEAM TURBINE WITH TWO-PHASE ALTERNATING CURRENT DYNAMO, 300 H. P., 200 K. W.

In Germany the same size machine is mounted on top of the boiler in front of the cab, a suitable sheet-iron cover is placed over the entire unit, and a small switch board in the cab controls the lighting system.

This turbine has not yet been used for marine propulsion, but has been adopted by many of the foreign navies and some of the trans-Atlantic liners for the lighting of the vessels. The small space and comparative lightness of the units allow of their being placed upon a shelf at the side of the engine room.

Another use is with fan blowers, to which the turbine is directly connected. These are suitable for gas works and blast furnaces.

One of the most interesting applications is in connection with the De Laval centrifugal pumps. The high available speeds at which these can be driven open a new field in centrifugal work. The pumps are made in standard sizes for heads up to 500 feet, and can be made for higher lifts if need be.

For low pressure work, with heads 250 feet and under, a simple pump is used, or a double pump operated either in parallel or series, as the case demands. These pumps are extremely simple, having a composition runner with properly designed inlet and outlet orifices. The bearings are of the ring oil type, and are separate from the stuffing boxes. A pair of these low pressure pumps is being installed at the filtration plant of Providence. These are 50 horse power each, and will deliver 20,000,000 gallons per day at a 7-foot head. They are directly connected to motors which receive their current from a turbine generating set at the pumping station.

The high pressure pump, however, is the greatest novelty. This consists of two separate pumps. Here the geared shaft running at 1,200 revolutions per minute, with a pump runner about 12 inches in diameter, lifts the water to the second pump, which carries a runner about 4 inches in diameter; this revolves at 12,000 revolutions per minute, being directly fixed upon the turbine wheel shaft. This size, 100 horse power, will pump 530 gallons per minute against a pressure of 215 pounds. There is a T connection between the pumps, with one side blanked off. From this point water can be taken to a condenser, the water so used being returned again below the inlet of the low pressure pump. This makes an ideal unit for water works, since the cost of maintenance is extremely small, and the first cost very little compared with high duty pumps. Of course centrifugal pumps are limited to about 80 per cent efficiency, yet this generally figures a large saving

when compared to the initial cost and maintenance of the *high duty* type.

The De Laval steam turbine may be seen in operation at the New England Structural Company's works in East Everett, where there are two 100-kilowatt units, 250 volts on each armature, running at a speed of 1,200 revolutions per minute. The two generators of each turbine are in series, and a three-wire 250–500 volt system is used. Here the lights are on the lower potential and the motors on the higher. There being several cranes electrically operated, the load is subject to sudden fluctuations, which are easily taken care of by the throttling governor. Stirling boilers for 150 pounds gauge pressure deliver practically dry steam to the turbines. A jet condenser gives a vacuum of about 27 inches, while two heaters are used, one supplied by the exhaust steam of the turbines, and the other by that of the auxiliaries. Six inches of concrete set upon the floor comprise the foundations, while the units rest upon these without being bolted down. On the wall a large oil tank feeds the oil to the turbine bearings. It is a plant well worth seeing, and is but a short distance from Boston.

THE APPLICATIONS OF ELECTRICITY TO METALLURGY.

By JOSEPH W. RICHARDS, A.C., Ph.D.

(Read January 15, 1904.)

Metallurgy is the art of extracting metals from their ores; of refining them to the purity required by the metal industries; and of melting, alloying, casting, and working them into the forms needed by the manufacturer of metallic articles.

The metallurgist takes the ore from the miner; this is his raw material, and he furnishes the metal to the various industries in the form of ingots, slabs, rods, bars, or castings. The workman who by cunning craft transforms these crude forms into articles of use or beauty is a metal worker, but not a metallurgist in the sense in which I am using the term.

The operations of metallurgy are mechanical and chemical. A few of the metals occur in the bosom of mother earth in the native, metallic condition. Such are particularly gold, silver, platinum, copper, arsenic, antimony, and bismuth. The treatment of these ores is not necessarily chemical. The metal may in any of these cases be extracted from the mass of ore by crushing and mechanical concentration, or by melting out, or by vaporization. Such are purely physical or mechanical processes.

The other metals, and indeed all of the above also, except gold, platinum, and bismuth, occur in largest quantity in nature as chemical compounds, which are broadly divisible into two classes: sulphur compounds and oxygen compounds. The extraction of the useful metal from these compounds is essentially a chemical problem, using mechanical processes such as concentration or grinding, or physical processes such as melting and vaporizing, as accessories. The question confronting the metallurgist in these cases is, "How can I most cheaply decompose this chemical compound and bring forth the metal in the free state?"

The answer to this query has been the devising of chemical processes of the most diverse and interesting character. Oxidized ores are commonly reduced by the agency of carbon or its first derivative, carbonic oxide gas, illustrations of which are our huge blast furnaces for reducing iron ores; the more modest cupola smelters for lead, copper, and tin; the complicated retort furnace, with condensers attached, for zinc; the expensive crucible method for manganese and chromium. Some oxidized ores, as of aluminum, magnesium, calcium, barium, and strontium, are not reducible by carbon at ordinary furnace heats, and the metallurgist has isolated these metals only by attacking the question in flank, and converting these oxides first into chlorides or fluorides and then decomposing these by stronger metals, such as sodium or potassium.

The sulphides as a class are not decomposable by carbon, but they are fortunately all convertible into oxides by roasting them at redness in a current of air, and the oxide formed may then be reduced in the same way as an oxidized ore. The sulphide of mercury is exceptional in that it roasts directly to metallic mercury vapor, which needs only condensation.

Of the common metals, the following are their most common ores:

Iron	oxides	Bismuth	native
Lead	sulphide	Magnesium	carbonate
Zinc	sulphide	Chromium	oxide
Antimony	sulphide	Tungsten	oxides
Copper	sulphides	Titanium	oxide
Tin	oxide	Molybdenum	sulphide
Aluminum	oxide	Vanadium	oxide
Nickel	sulphide	Cadmium	sulphide
Mercury	sulphide	Uranium	oxide
Gold	native	Cobalt	arsenide
Silver	sulphides	Tellurium	tellurides
		Platinum	native

Electricity is used to assist the metallurgist in three fundamentally different ways, viz.: I. Mechanically. II. Thermally. III. Electrolytically.

I. Mechanical Applications. — The mechanical assistance of electricity is here meant as not including the ordinary electric devices, such as elevators, cranes, motors, etc., but is intended to include all those mechanical processes, which when applied to ore or metal, aid

in its extraction. It refers particularly to the electro-magnetic and electrostatic concentration of the heavy metallic parts of ores, with the rejecting of the worthless gangue material.

A treatise might be written, in fact has been written, upon this subject alone. Within less than a year F. Langguth has published a monograph on "Elektromagnetische Aufbereitung,"[1] which describes at length the various electro-magnetic processes for dressing and concentrating ores. This branch of electro-metallurgy is already rendering important service to the iron industry in making it possible to use ores which were otherwise too lean or too impure to be put into the blast furnace, and has thus added largely to our available supplies of iron ore.

A principle differing from the time-honored electro-magnetic concentration is the electrostatic process, based on the repelling force of electrostatically charged particles, devised by Blake and Morscher. The machine and process are described, with illustrations, by Swart, in the *Engineering and Mining Journal* for January 24, 1903. When the mass of ore and gangue particles is brought into contact with a statically charged metallic surface, particles of low conductivity become charged and repelled, while those of high conductivity are not repelled. Some interesting separations, differing radically from electro-magnetic separations or specific gravity separations, can be thus accomplished. As a general rule, the metallic compounds present, as sulphides, etc., are good conductors, while the gangue of quartz, lime, etc., is a poor conductor; but there are interesting exceptions, such as zinc blende, which is a poor conductor, and can be thus separated from pyrite, galena, and chalcopyrite, or from magnetite and pyrrhotite, dryness being the only requirement and proper sizing. A one horse power static machine, generating current at 10,000 to 20,000 volts, will treat 12 to 15 tons in twenty-four hours. This process is therefore a mechanical separation on a newly applied electrical principle, and gives promise of being extremely useful to the metallurgist in some special cases, such as the treatment of mixed complex sulphide ores.

II. Thermal Methods. — The electro-thermal processes useful to the metallurgist are numerous and important.[2] In them the energy of the electric current is converted into heat, and the processes are either merely mechanical processes, such as melting, volatilization or

[1] Published by W. Knapp, Halle.

[2] This class of furnaces is thoroughly discussed by W. Borchers, *Die Elektrische Oefen*, Halle, 1895.

heating alone; or chemical processes, such as purification of ore, or reduction to metal, in which the electric current acts simply as the source of the heat needed. Since the chemically decomposing or electrolytic effect of the current is not utilized in this class of processes, they ordinarily operate quite as effectively and efficiently with an alternating electric current as with a direct; in fact, there is a decided preference in this line for using only alternating current, since it is more manageable and easier to obtain.

We may divide these electro-thermal metallurgical operations into two classes, viz., those operating by an arc and those operating only by the incandescence of an electrically heated conductor.

The first class, the arc furnaces, are not so extensively used as the second class. Henri Moissan has been the chief investigator of the possibilities of the arc furnaces, and in his classical work [1] has given us the results of using various forms for different chemical and metallurgical operations. But long before him, pioneers in electro-metallurgy had devised and patented similar operations. Pichon, in 1854, proposed to feed a mixture of metallic ore and carbon into the space between two powerful arc light carbons, and thus smelt the ore. Siemens, in 1879, proposed to melt steel by making it one pole of a powerful arc, in a crucible, and actually operated a furnace on that principle, but it was not commercially profitable. Captain Stassano, in Italy, has recently operated a furnace resembling a small blast furnace, in which the heating agent was a powerful electric arc placed just above the crucible of the furnace, which, partly by contact with the charge but more by radiation and conduction, heated the iron ore, carbon, and fluxes charged to the necessary temperature to produce fluid steel and slag. This method also has not as yet been applied profitably to the reduction of iron ores, but its application to the reduction of copper ores, where power can be had cheaply and fuel is dear, is more promising. An older idea is to mix the ore to be reduced with carbon and to compress it into solid electrodes, which are then used as the terminals of an arc, and the smelting takes place in the arc itself, while reduction may take place in the body of the carbons just a little back of the terminals and the extreme temperature of the arc.

Several electric furnaces now in practical application unite the heating by arc and by incandescence. Such is the melting and purification

[1] *Le Four Electrique*, par Henri Moissan, Paris, 1897.

process for purifying bauxite used by Mr. Hall. The aluminum ore, mixed with sufficient carbon to reduce its impurities, is fed into the vicinity of very powerful arcs, where it is fused by contact and the radiated heat. The fused mixture falling beneath the arc becomes the other pole, and is subsequently kept melted and enabled to complete its reaction by the passage of the current through it. In this way a body of material several feet deep can be kept in fusion while the actual fusion to start with is affected at the surface of the bath by the heat of the arcs springing to its surface from the overhanging carbons. This method is very effective in localizing heat where it is needed in greatest amount, and yet distributing a part of it through a large body to maintain it in fusion after it is once melted.

The chief difficulty in managing arc furnaces is the variability in the resistance of the arc, caused by irregularities in the wearing away of the terminals, and by foreign material bridging over from time to time. These variations are trying on the electrical machinery, and tend to reduce the efficiency of the operation as a commercial process.

Heating by incandescence is the more largely applied principle in electric furnaces. Before describing this class of operations we must clear the ground by limiting the incandescence to that of conductors which are not being used as electrolytes, else otherwise we would pass in our description to the "electrolytic" metallurgical processes, which are of a fundamentally different character from the electro-thermal processes now under discussion. The operations now being discussed, in which the current acts only as a heating agent and does not perform electrolysis, are called "electric furnace processes"; those electrolytic processes, of our third class, in which heating is essential and is incidentally supplied by the energy of the current performing electrolysis, are called "electrolytic furnace processes." The latter must be discussed in their own class, because of the essential electrolytic character of the operations produced in them.

Electro-thermal, or electric-furnace, processes are extremely useful to the metallurgist, and may take many forms. They may be used in the form of the incandescence of solid or liquid conductors, the former continuous or granular, and used for simple heating, melting, or for provoking chemical reactions.

Using solid conductors of carbon or a difficultly fusible metal, we have the electrically heated muffles or crucibles, which have the conductors wound around them or embedded in their sides, and which are

so useful in the laboratory and for performing metallurgical operations on a small scale with an exact regulation of temperature, such as tempering steel and making alloys. Again, if the material to be treated is packed around the solid conductor it may be heated up to its reacting point by the heat radiated and conducted from the incandescent conductor. Such operations were conducted on many difficultly reducible oxides by W. Borchers, in 1892, by using a thin pencil of electric light carbon as the heat producer, and packing around it the oxide to be reduced mixed with carbon. In this way all the metallic oxides are capable of being reduced, and the process is at present commercially applied to reducing tungsten, titanium, and similar metals which cannot be reduced by carbon at ordinary furnace heats. The production of carborundum by heating a mixture of silica with carbon in excess, by the use of a solid carbon conductor 4 inches square, is an application of the incandescent electric-furnace principle; but the operation is one belonging to the field of industrial chemistry, and not to metallurgy, since the product is not metallic silicon, but silicon carbide, and the operation is therefore not a metallurgical operation nor part of the metallurgical industry.

Quite recently Mr. F. J. Tone, of Niagara Falls, has devised a furnace for the reduction of oxides whose temperature of volatilization lies close to the temperature of reduction. This furnace contains a vertical column of carbon blocks piled upon each other, and forming practically a solid carbon core, around which is the mixture of fine carbon and the oxide to be reduced. As the reduction of the charge proceeds, being heated up to the reacting temperature by the incandescent core, the reduced metal trickles down the furnace and thus escapes from the intense heat as fast as it is reduced. This pretty metallurgical operation has already resulted in the production of metallic silicon at a low cost. I have seen two heavy barrels full which Mr. Tone has made,[1] and the principal difficulty now is to find commercial uses for this pure silicon at a reasonable selling price.

Some very important developments are now being made in the utilization of electric furnaces with fused metallic conductors. Such are the many forms of furnaces now in use for producing steel. An entire evening would be none too long for describing the present condition of the electric-furnace production of steel. Various ways of

[1] A large piece weighing several pounds was exhibited at the lecture.

applying the current have been tried, but the most successful are those in which the steel itself, lying in a long trough or gutter, forms the resistance material and conducts the heating current.

In the Gin furnace[1] the trough has a serpentine course, passing several times up and down the length of the furnace hearth, and being tapped at the bends. The terminals are large blocks of steel, which from their size remain solid, and are also prevented from melting by being water cooled. The operation is that of the ordinary open-hearth process, except that oxidation is produced entirely by iron ore instead of by air, and the quality of the steel is claimed to be equal to crucible steel. It is claimed also that steel can be thus made, using power at twenty dollars per horse power year, at lower prices than by present open-hearth methods.

The Kjellin furnace[2] is based on the use of liquid steel itself as resistance, but embodies the brilliant idea of shaping the trough of steel into a circle, and heating it by induced currents alone, the ring of steel being the secondary circuit of a transformer, of which the primary is a heavy coil encircling a magnet, one pole of which passes through a hole in the centre of the furnace. The output is reported to be 100 pounds of steel per kilo-watt day, which amounts to only two dollars per ton of steel for power.

There is not the slightest doubt that within a short time electric steel furnaces will be as numerous as ordinary open-hearth steel furnaces, and, in the writer's opinion, the days of the crucible steel process are numbered, for the electric furnace can already compete in any locality with the crucible furnace for manufacturing high grade and special steels.

A very effective means of diffusing the heat-developing power of the current passing through a conductor, so as to heat up a large space, is to break up the conductor into a large number of irregular fragments, as by using it in a granular condition, for instance, and then to pass the current through it. Under these conditions the current passes from piece to piece through innumerable contact points; and since these are points rather than surfaces, the local resistance at the contacts is very high, and a great development of heat is pos-

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[1] As described at length by Mr. McN. Bennie, in *Electro-chemical Industry* for January, 1904, p. 20.

[2] Description in *Electro-chemical Industry*, December, 1903, p. 576.

sible from a relatively small weight of resistance material. Ball and Guest used this principle in 1883 to bake incandescent light filaments, which they embedded in granular carbon and then passed an electric current through the latter. In 1893, E. G. Acheson used the same principle in making carborundum, the granular carbon taking the form of a cylindrical core around which the carborundum producing charge was placed, and the heat developed in the core raised the surrounding charge to the reacting temperature. Neither of these was a metallurgical operation, and the credit of applying this principle to metallurgical processes belongs to E. and A. E. Cowles, who, in 1885, invented the process of mixing the granular resistance material with the ore to be reduced and passing an electric current through the mixture, whereby the ore was in intimate contact with the electrically heated resistance material, and therefore immediately subjected to the electrical heat at the point of its generation. The process, its mode of operation, and its results were very thoroughly described by my friend, Mr. Cowles, before this Society, as set forth in your PROCEEDINGS for 1885–86, page 74.

The method of operation of this process is familiar to probably every one. On account of the intensity of the heat to which the charge is raised, volatile metals can be obtained as alloys only, by mixing a less volatile metal or its oxide in the charge. Thus the Cowles Company produced aluminum-alloys with copper and iron, copper-alloys with silicon, and other such alloys, but could not produce pure aluminum or silicon in this manner. Within the last few years this method of operation has been extensively adopted for producing alloys of iron with manganese, silicon, chromium, tungsten, molybdenum, vanadium, boron, etc., for use in the manufacture of special steels. In producing these alloys, which require a high temperature for reduction, the electric furnace has already gained a commercial position which makes it an important factor in the iron industry.

The particular advantages of electric-furnace heat are:

1. It can be generated up to 3,500° C., which is at least 1,500° higher than can be obtained in fuel-fed furnaces.

2. It is applied internally, or in such close contact with the material to be heated that it is greatly more efficiently applied than the ordinary forms of heating.

One horse-power-year costs from ten dollars to twenty-five dollars at established water power installations, and its heat-producing power is

15,000 calories per day, or the equivalent of the full calorific power of 2 kilos of good coal. This gives the heating power of a horse-power-year as that of 730 kilos, or three-quarters of a ton of coal. But for a given heating effect the electric heat can be applied (for instance, to melting steel) at an efficiency of 75 per cent., whereas the heat of combustion of coal is at most applied at an efficiency of 25 per cent. We may say, therefore, in general, that the electric heating will cost less where coal costs per ton over one-half of the price paid per electrical horse-power-year. This is on the assumption that coal can be so used as to produce the effect desired, and ignoring many other advantages which electrical heating possesses, and which in many cases make its use preferable even at several times the cost of a ton of fuel per horse-power-year.

III. Electrolytic Methods. — These are the processes where the chemical decomposing power of the current, its ability to perform electrolysis, is utilized. They may be all classed under three heads:

1. The material being treated is the electrolyte, or part of the electrolyte.

2. The material being treated is the anode, or placed in contact with the anode.

3. The material being treated is the cathode, or placed in contact with the cathode.

The electrolyte may be a solution in water or a fused salt.

We will discuss first the phenomena of electrolysis and its attendant chemical phenomena, in order to understand the principles of action which the metallurgist has at his command in employing electrolysis.

When a direct electric current passes through a liquid compound body it tends to separate it into two integral parts, its positive and negative constituents, or, otherwise stated, its metallic base and its acid radical. The water of an aqueous solution is never decomposed primarily so long as there is sufficient salt in the solution to carry the impressed current, no matter how much stronger a compound than water the dissolved salt may be.

This primary electrolysis is a simple decomposition of the compound into two primary constituents, which are liberated at the surface of the two electrodes whereat the current enters and leaves the electrolyte — points which may be placed a fraction of an inch apart, or 30 feet or a mile apart, if the apparatus is of that size.

The constituents tending to be liberated, the acid radical at one

pole and the basic metal at the other, may be liberated actually as such, or they may, by simultaneously reacting upon the electrodes or upon the electrolyte in contact with the electrodes, give rise to so-called secondary actions, whereby the ultimate results of the passage of the current are the ultimate products thus developed. It is important that we recognize clearly what the tendency or characteristics of these secondary reactions are at the two poles. At the cathode, the basic metal tending to be set free, the electro-positive constituent of the compound primarily decomposed exerts, on the cathode, or, on the electrolyte itself, a chemical *reducing* action, tending to decompose compounds of weaker metals, and by abstracting or uniting with their acid constituent to set their base free. If, therefore, the metallic compound to be acted upon is made the cathode, or brought into intimate contact with the cathode, the tendency of the passage of the current is to abstract its acid constituent and to leave its base free *in situ.*

If, on the other hand, we consider the action at the anode, the acid radical, which tends to be liberated there, exerts upon the anode or upon any substance in contact with it the exact opposite of a reducing effect, namely, an acidifying or (to use a recently coined term) a *perducing* effect, corresponding to what chemists indicate by "oxidation," used in the general sense of increasing the amount of acid constituent in a compound. The tendency on a metal used as anode, or, in intimate contact with the anode, is to take it into combination, by which it becomes, in general, part and parcel of the electrolyte itself, and is ultimately deposited out upon the cathode; upon a metallic compound thus used the tendency is to extract its base and leave its acid constituent free, in place of the acid radical which would have been liberated by the primary action of the current. The action at the anode, in fact, is analogous to the action of the concentrated acid corresponding to the acid radical being liberated by the primary decomposition of the electrolyte, but is in general much more intense. The action, finally, may be described as the exact opposite of the secondary action at the cathode, since the tendency of the action on a metallic compound is here to extract its basic constituent and to leave its acid constituent free *in situ.*

With these preliminary ideas fixed in mind, we will discuss the *three principles* on which electrolytic methods are useful to the metallurgist, and their applications.

The use of the material under treatment as the electrolyte, or

part of the electrolyte, is a fruitful source of electro-metallurgical processes, and has given to us electrolytic sodium, potassium, lithium, calcium, barium, magnesium, aluminum, manganese, titanium, chromium, and several other metals. The principle may be applied in two different ways: thus, first, if a fusible compound of the metal desired is easily obtainable, that compound may be directly fused and electrolyzed. This was the principle on which Sir Humphry Davy obtained sodium and potassium from their fused hydrates, Bunsen obtained magnesium and aluminum from the fused chlorides, Deville obtained aluminum from its fluoride mixed with sodium fluoride, Guntz obtained lithium from its fused chloride, and Ashcroft and Swinburne have recently extracted zinc on a commercial scale from its fused chloride. In fact, any fusible salt of a metal which can be easily produced may thus serve as the basis of an electrolytic method for the extraction of the metal, the latter being obtained in the solid, liquid, or gaseous state, according to the temperature at which the electrolysis takes place, and the metal in the liquid state either sinking to the bottom of the bath or floating on top, according to the relative specific gravities of the fused metal and fused salt.

In thus electrolyzing a fused metallic salt it is almost an invariable rule that the output of metal will represent more nearly 100 per cent. efficiency on the amperes, the nearer to its melting point the salt is when electrolyzed. In electrolyzing fused lead chloride, for instance, Beetz obtained 99.8 per cent. efficiency on the current used at the melting point, only 50 per cent. efficiency at 150° above the melting point, and practically no metal at nearly the boiling point of the salt. In electrolyzing fused caustic soda to produce metallic sodium, the output falls rapidly from about 90 per cent. within 10° of the melting point (309°), to zero at 25° above the melting point. Mr. Castner, the inventor of this latter process, claims in his patent merely the electrolysis of fused caustic soda at a temperature within 25° C. of its melting point, and has thus covered what he had found to be the one practical condition necessary in order to obtain the metal from that salt.

As regards the power necessary for this electrolysis, the direct electric current is, as a chemical decomposing agent, practically omnipotent. A drop of potential of five volts from one electrode to the other, in addition to the ordinary voltage necessary to send current through the bath considered merely as a conductor, is sufficient to decompose

the strongest chemical compound known, while the average chemical compound absorbs only one to two volts per bath. Expressing this in another way, which may appeal more plainly to the electrician, if a given bath will pass 10,000 amperes of *alternating* current with a drop of potential of three volts, and no decomposition taking place, it will pass 10,000 amperes of *direct* current with a total drop of between three and eight volts, and with total decomposition of the bath occurring.

The output of metal is proportional to the amperes of current passing, according to Faraday's laws. The drop of potential due to the ohmic resistance of the bath is also proportional to the amperes of current passing, and to the resistance of the bath considered merely as an electric conductor, the same as if it were a bath of mercury of a given length, breadth, and depth, and of known specific resistance or conductivity. The formula would be $V^c = AR$, where V^c is the voltage lost in overcoming ohmic resistance, A the amperes passing, and R the total ohmic resistance of the bath.

The drop of potential due directly to decomposition (V^d) depends on the strength of the compound decomposed, and is entirely independent of the ohmic resistance of the bath or the amperes of current flowing through it. It is numerically equal to the heat of formation of the compound being decomposed at the temperature used, expressed per one chemical equivalent of its components in grams, divided by 23,040. The latter quantity, 23,040 calories, is the thermo-chemical equivalent of the work done in the liberation of one gram equivalent of a metal, per one volt drop of potential used in decomposition.

If a fusible compound of the metal desired is not readily obtainable, or a suitable one not to be found, the problem of decomposing a practicably infusible compound may be solved by the beautiful principle discovered and illustrated in Hall's process for obtaining aluminum. The most abundant source of aluminum is its oxide, alumina, but this is not fusible except at electric-furnace heat at a temperature at which aluminum itself volatilizes. Hall sought for a fusible salt which would dissolve alumina and be electrically more stable than alumina. After long search he discovered this solvent in a mixture of fused sodium fluoride and aluminum fluoride, both of which salts are chemically and electrically more stable than alumina. By passing the direct current through the solution of alumina in this bath only the former is decomposed, yielding its products at the electrodes, and the process is made continuous by supplying fresh alumina as the bath becomes impover-

ished thereof. The discovery of this principle of working has established the aluminum industry, which is now using in America alone 22,000 horse power, and producing 4,000 tons of metal annually.

I am surprised that the same principle, within the large variations which it permits, has not been applied to the reduction of other metallic oxides. It is certain that easily fusible silicates of manganese and calcium, for instance, would dissolve manganese oxide to a considerable extent, which would be decomposed by the passage of the current. Any chemist could sit down and in a half-hour excogitate a whole series of possible applications of this principle which would need only simple experiments to test them. I consider this one of the most promising fields for experiment in the whole realm of electro-metallurgy.

This class also includes the electrolysis of aqueous metallic solutions where the metal is to be extracted only from the solution. Examples are the electrolytic precipitation of copper from waste copper sulphate solutions, usually using soluble iron anodes, in which latter case the solution of the anode furnishes enough energy to more than supply the necessary potential for the precipitation of the copper. Another use is the precipitation of gold from cyanide solutions by the Siemens-Halske process, where iron anodes are used which are corroded to iron cyanide.

In general, all the metals which do not decompose water in a finely divided state may be thus electrolytically deposited from solution, and the operation takes less power when soluble anodes of preferably a more positive metal are used. If soluble anodes of a less positive metal are used, it is necessary to use a porous diaphragm to keep the solution formed around the anode from contact with the cathode, else otherwise the less positive metal would then be deposited along with or instead of the metal which it was the purpose of the process to extract.

Passing on to the utilization of the so-called secondary actions at the anode, or, as I would prefer to say, to the acidifying or *perducing* influence of the passing of the current upon the anode or a substance in contact with it, we have only a limited number of applications so far made. The principal one is in the metallurgy of copper, where copper matte, practically copper sub-sulphide, Cu_2S, has been used itself as an anode in a solution of copper sulphate. The perducing or acidifying action extracts the copper from the matte, which goes into solution as $CuSO_4$, and is then plated out on the cathode, while the sulphur, being insoluble, is left *in situ*. The process was worked for some

time by Marchesi, at Genoa, but has been abandoned on account of the mechanical difficulties connected with the disintegration of the anode. A similar principle has been used by Frasch for attacking nickel-copper matte, the electrolyte being a solution of sodium chloride, and the matte being broken up small and laid upon a carbon anode, and thus subjected to the influence of the evolved chlorine *in statu nascendi*. This method is now being tested by the International Nickel Company for treating the Sudbury nickel mattes.

Solution of the anode is also the basis of the electrolytic refining processes by which impure metal is refined. The latter being used as anode, in a solution whose acid radical would form with the desired metal a soluble salt, the desired metal is attacked and dissolved, also any more electro-positive metals which form soluble salts, while metals which form insoluble salts with the acid radical, and also metals unattackable by it, remain undissolved and fall to the bottom as anode residue. By the use of proper current density and brisk circulation at the cathode, only the desired metal is precipitated out by the electric current, while the other more positive metals remain in solution. A fractional part of the solution is removed periodically and purified chemically or electrolytically, and thus the indefinite accumulation of impurities in the bath prevented.

Copper alone to the value of $100,000,000 is being thus refined annually, while silver, gold, nickel, antimony, zinc, and bismuth are also refined by analogous methods, also amounting in value to millions of dollars annually. It has been suggested, and the process patented, to refine aluminum, using it as a melted anode in a fused salt as electrolyte, but the process has not been industrially applied to my knowledge. It is interesting, however, as opening up another method of electrolytic refining.

The last principle, that of using the material to be treated as a cathode, or in contact with the cathode, is a principle first applied industrially by Mr. Pedro G. Salom, of Philadelphia.[1]. He was experimenting with storage batteries, and devised a method of producing spongy lead from native lead sulphide, galena. The electrolyte is dilute sulphuric acid; the anode and the cathode are sheets of hard lead containing antimony; the pulverized galena is placed in a layer $\frac{1}{8}$ inch thick on the horizontal cathode. On passing a current of thirty amperes per

[1] Description and illustration of apparatus in Vol. IV, *Transactions of the American Electrochemical Society*, 1903.

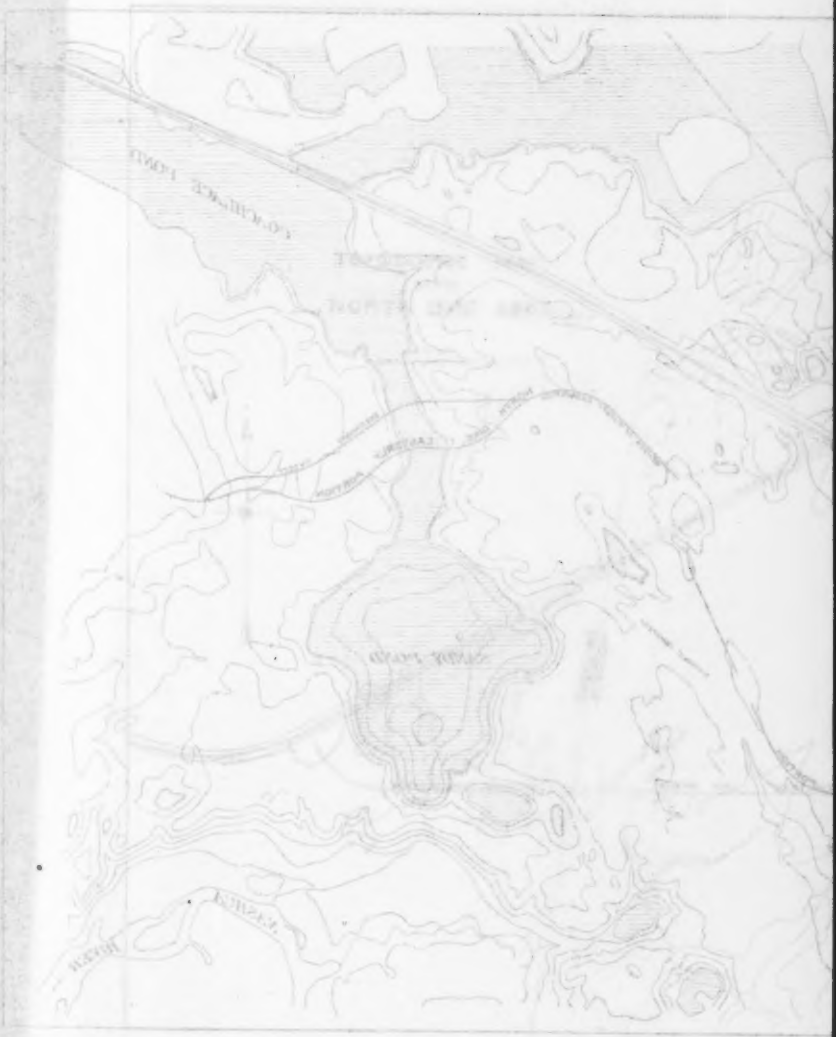
square foot of cathode, reduction of the galena takes place in one and one-half hours. The reducing action of the current removes the sulphur as hydrogen sulphide gas, leaving the resulting spongy lead *in situ*. The efficiency of reduction is shown by the fact that 98 per cent. of the ore will be thus reduced to spongy, metallic lead. Copper sulphide and silver sulphide are also reducible in a similar way; mercuric sulphide and zinc blende are not reducible, apparently because they are practically non-conductors.

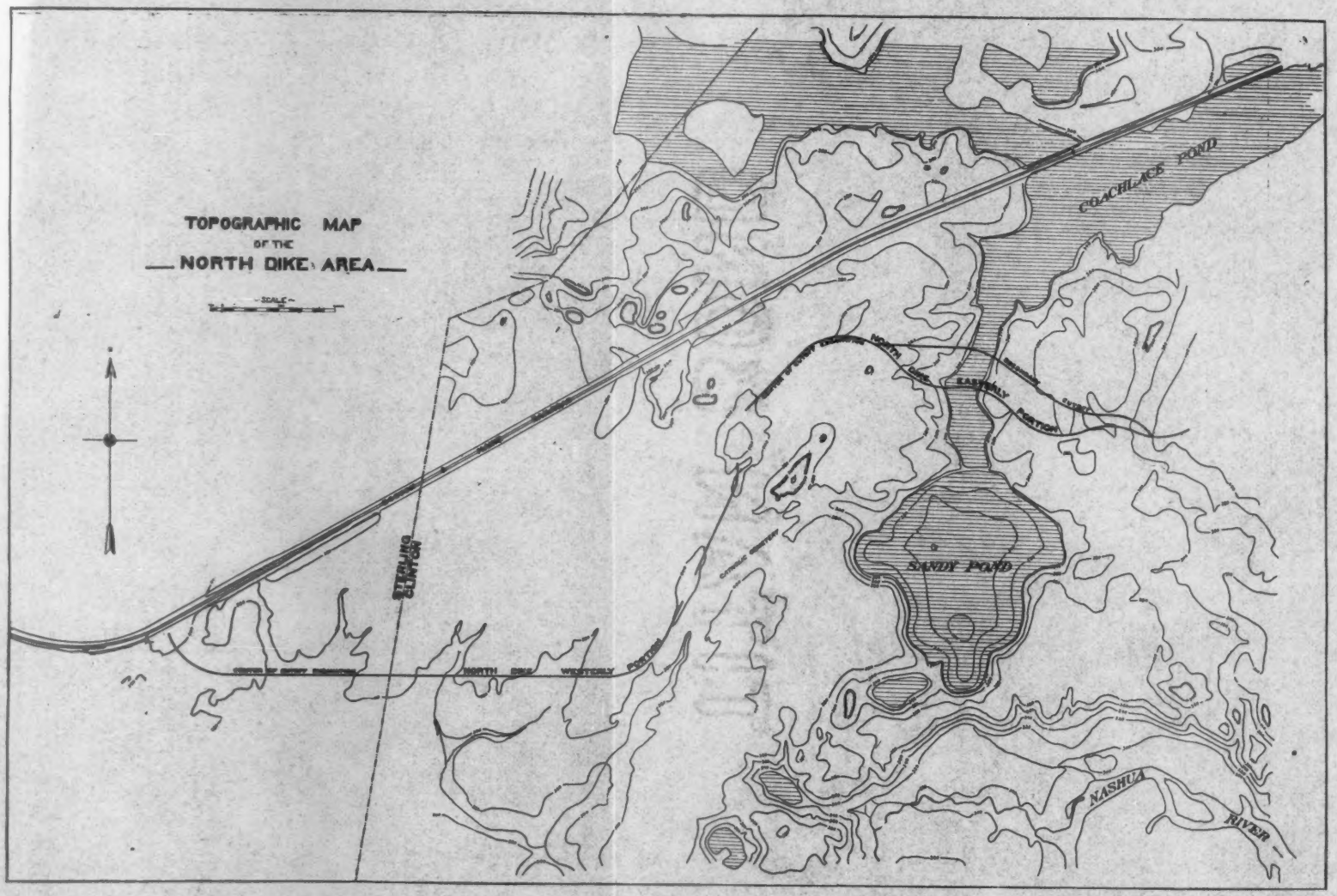
It appears, therefore, that the metallic compounds thus treated must be electrically conductive in order to be reduced; in fact, they become themselves the immediate cathode during the electrolysis. There is no reason why other metallic compounds which are conductors may not be similarly reduced. In fact, every one is familiar with the fact that in the discharge of the storage battery the lead peroxide on the negative plate, or cathode, is reduced to spongy lead.

The principle discovered by Mr. Salom is evidently one which may have a wide application.

While I have endeavored to classify the various electro-metallurgical processes, and to elucidate the broad principles on which they are based, yet I am conscious of the fact that I have by no means enumerated, much less described, all such processes. To do so would require a course of lectures instead of a single one. I have rather brought forward and described such typical processes as illustrated the various divisions of my classification.

But aside from the body of present processes included within this classification, there are undoubtedly many possible *applications* of these principles awaiting discovery by the patient investigator. Nay, more, it is altogether probable that there are new *principles* of electro-metallurgic action also awaiting discovery by the enthusiastic and imaginative investigator — principles whose first discovery will be the perquisites of investigators trained not only in manipulative skill, but also equally necessarily trained in "The Scientific Use of the Imagination."




TOPOGRAPHIC MAP
OF THE
NORTH DIKE AREA
SCALE
COACHICHE POND
SANDY POND
NASHUA
RIVER

STRUCTURE AND COMPOSITION OF THE DELTA PLAINS FORMED DURING THE CLINTON STAGE IN THE GLACIAL LAKE OF THE NASHUA VALLEY.

By W. O. CROSBY.

(*Continued from Vol. XVI, page 254.*)

Structural Features of the Clinton Plains.

It is proposed to consider here only that segment of the Clinton plains crossed by the North Dike, and bounded on the north by Coachlace Pond and on the south by Cunningham Brook and the Nashua River; for, as previously noted, this member alone of the Clinton series has been sufficiently dissected by borings and excavations to afford the data requisite to an understanding of its structure.

General Topographic and Bed-rock Relations. — As the contour maps clearly show, the North Dike plain is approximately two miles long (east-west) by one mile wide in the general direction of its growth from north to south, and divided midway of its length by the narrow and overlapping ridges of metamorphic slate or phyllite, on the most southerly of which the Catholic cemetery was formerly located. The western part of the plain is, in most respects, the more normal delta, at least in regard to its formal features — an almost unbroken plain sloping gently and evenly southward from a typical ice-contact margin fringed with kettles to a lobate frontal slope, which is separated from the ice-contact margin of the earlier Nashua plain by the foss valley of Cunningham Brook. In its lower surface, also, the western part of the North Dike plain is relatively simple and normal, since its northern half rests on an approximately plane bed-rock floor, ranging in elevation from about 330 to nearly 370 feet, which also slopes gently southward and is rather deeply trenched in that direction by several southward-sloping and southward-converging valleys. The form of the bed-rock surface, so far as developed by the borings, and the relation to it of the preglacial drainage lines and the surface of the delta

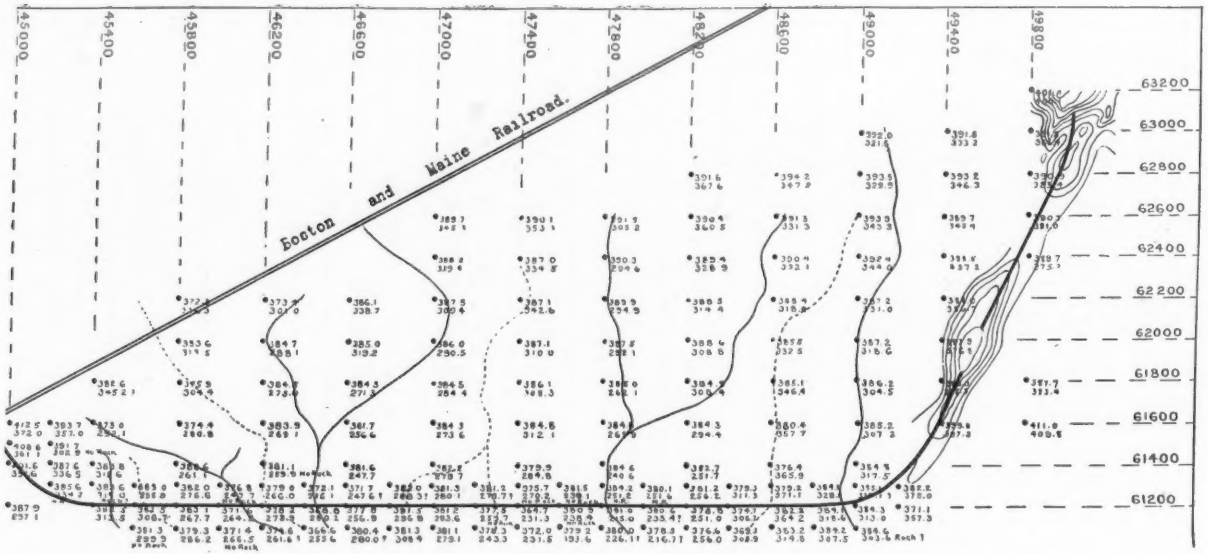


FIG. 10.—MAP SHOWING THE DISTRIBUTION OF BORINGS IN THE WESTERLY PORTION OF THE NORTH DIKE AREA.

Approximately one-half of the actual borings are represented, the alternate north-south lines of borings being omitted. The numbers accompanying the individual borings give in each case the elevation above sea level of the surface and of the bottom, the difference being the depth of the boring. The full lines represent the axes of bed-rock valleys, and the broken lines the crests of bed-rock ridges.

plain are exhibited in the map (Figure 10), although this shows only one-half of the borings, and still more clearly in the profiles, especially of the east-west series (Figure 12).

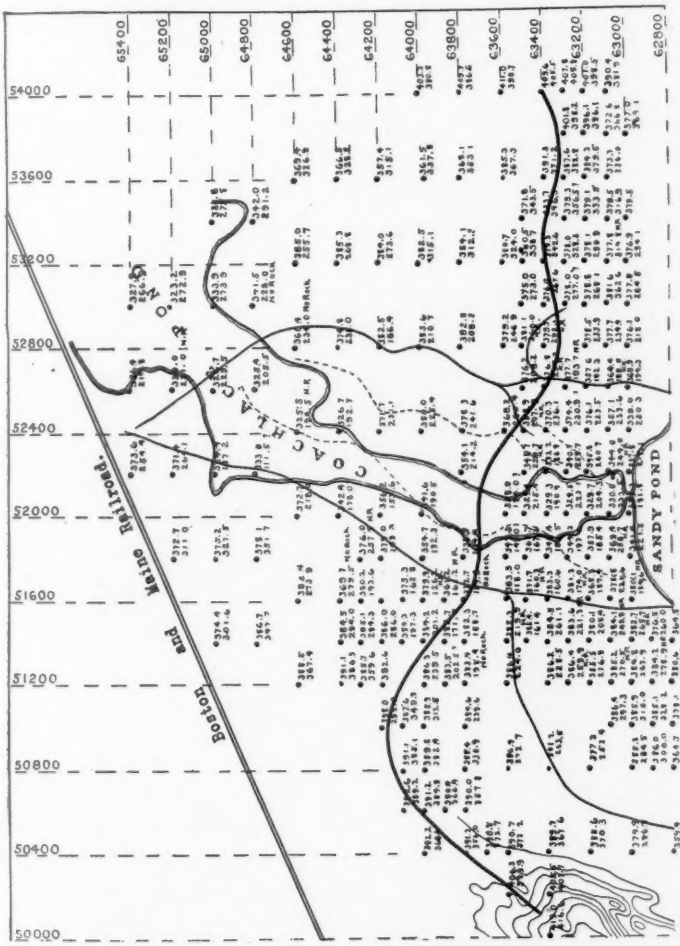


FIG. 11.—MAP SHOWING THE DISTRIBUTION OF BORINGS IN THE EASTERLY PORTION OF THE NORTH DIKE AREA.

Explanation same as for Figure 10.

The eastern part of the plain, as it existed before the building of the North Dike, is far more irregular both superficially and basally, as shown in Figure 11. Midway between the cemetery ridges and Burdette Hill it is widely divided by the kettle basins of Coachlace

and Sandy Ponds, continued southwestward in a string of more normal kettles; and approximately coincident in position and trend with this depression is the deep, preglacial bed-rock gorge of the Nashua River, to which several minor bed-rock valleys with separating ridges of schist are tributary.[1]

The most surprising and puzzling feature of the relations of this plain to the bed-rock contours is the fact that the basin or trough of Coachlace Pond, as it existed before the building of the North Dike, although closely parallel to the deep, buried gorge of the Nashua, does not directly overlie it, but is superposed, with 120 to 130 feet of modified drift intervening, upon a distinct bed-rock terrace several hundred feet wide, and with an elevation of 190 to 210 feet, separating the gorge from a well-defined ridge of schist comparable with the cemetery ridges and rising to a maximum elevation of 280 feet, or within 100 feet of the surface of the Clinton plain. This relation, whether fortuitous or not, clearly demands consideration in any discussion of the origin of the kettles. It appears from the foregoing, supplemented by the map (Figure 11) and the east-west profiles (Figure 14), that the broken eastern half of the North Dike plain rests upon an unusually rugged bed-rock topography, with a maximum relief of nearly 300 feet and corresponding variation in the depth or thickness of the modified drift; and it may be added that the form of the bed-rock surface is without appreciable influence upon the contours of the delta plains, except, perhaps, in determining in some degree the location and trend of the north-south line of kettles, or ice-block depressions. The bed rock beneath the modified drift is everywhere fresh and unweathered, even the pyrite cubes in the black, carbonaceous phyllite being bright and entirely unoxidized.

Relations to the Ground Moraine, or Till. — With a bed-rock topography of strong relief, the dominant trends of which are obliquely transverse to the direction of glacial movement, it might perhaps have been anticipated that the depressions would be deeply filled with the ground moraine. As a matter of fact, however, the borings show the valleys, and notably the deep, preglacial gorge of the Nashua River, to be remarkably free from till; and this notwithstanding that the North Dike plain terminates both east and west in prominent drumloids in which the bed rock is heavily covered with till. As the

[1] Technology Quarterly, 12, 294.

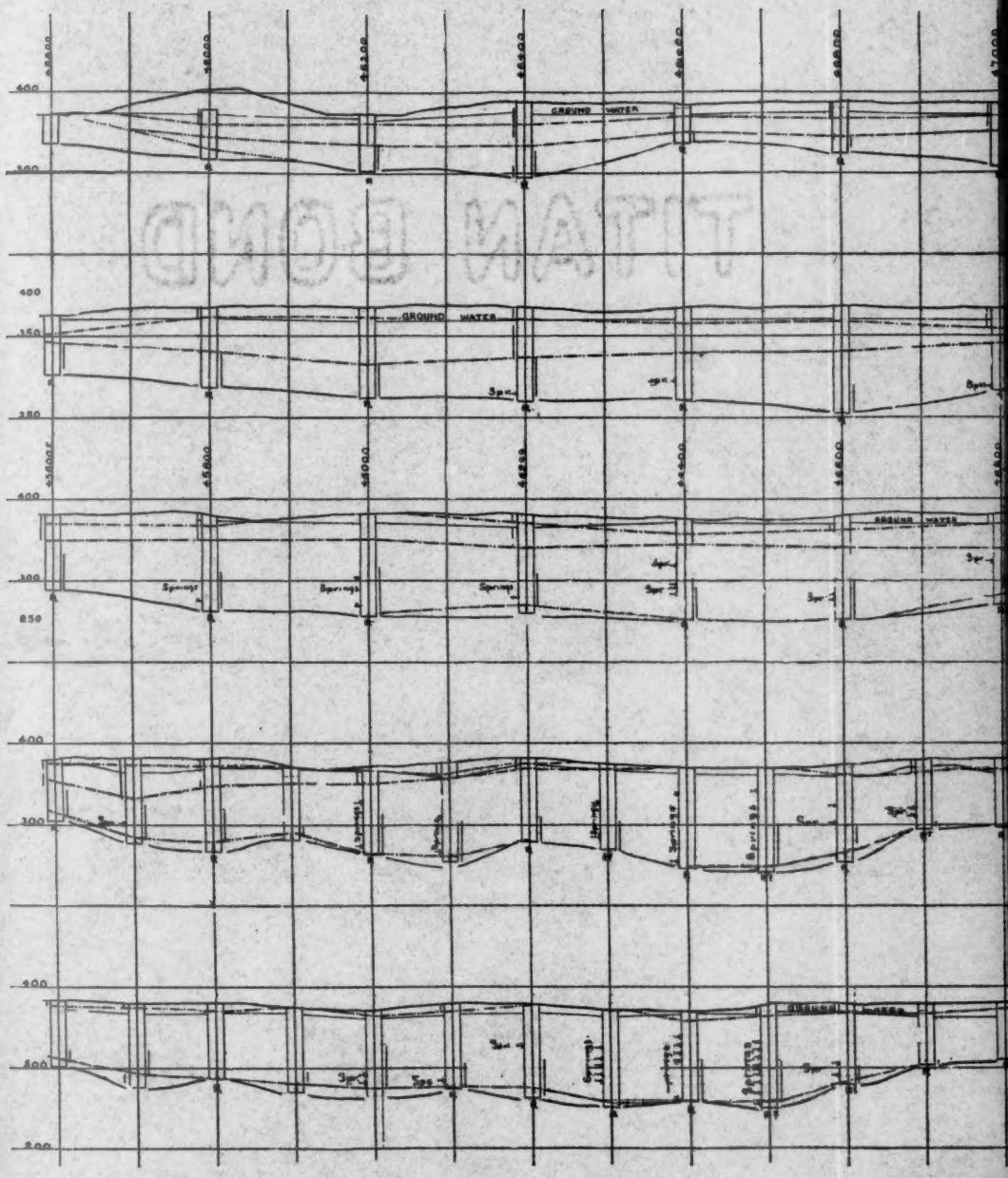
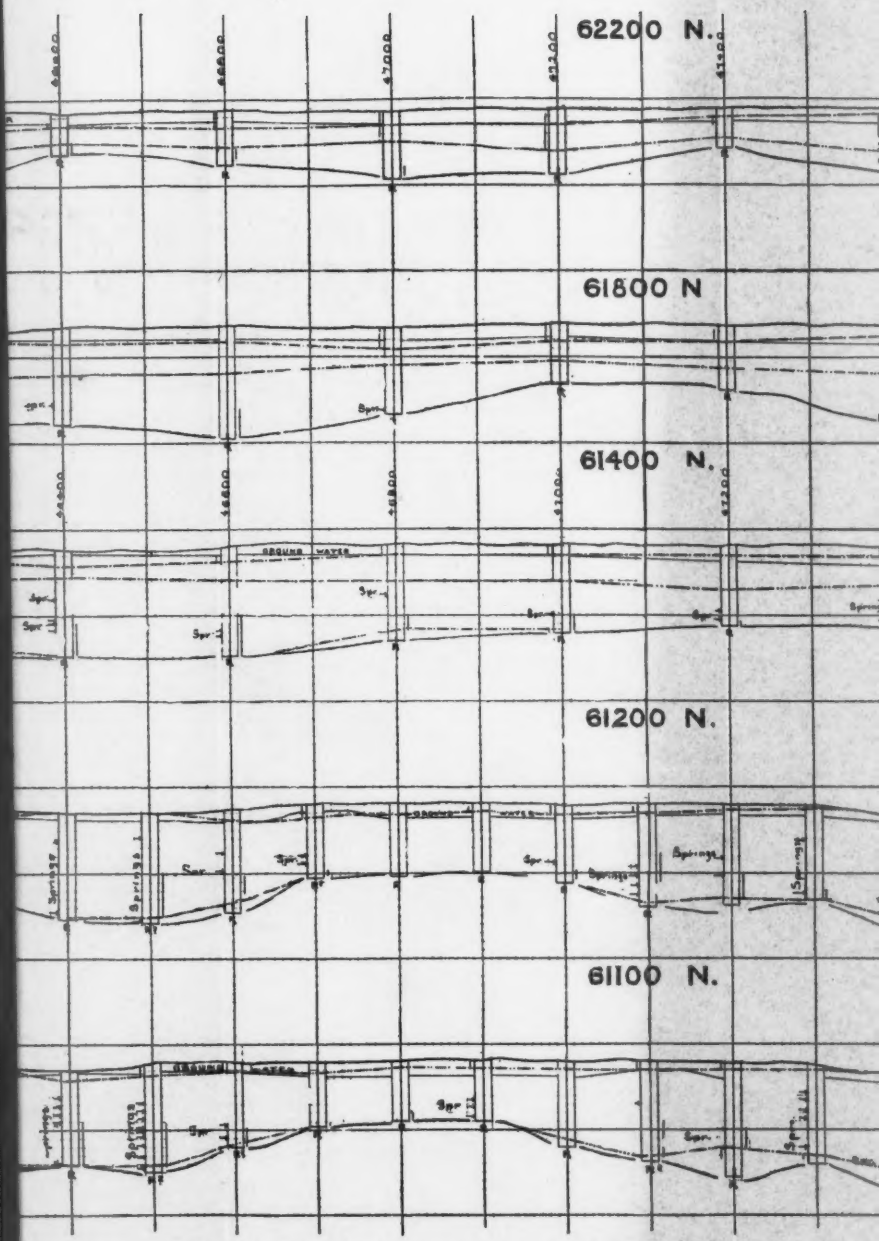


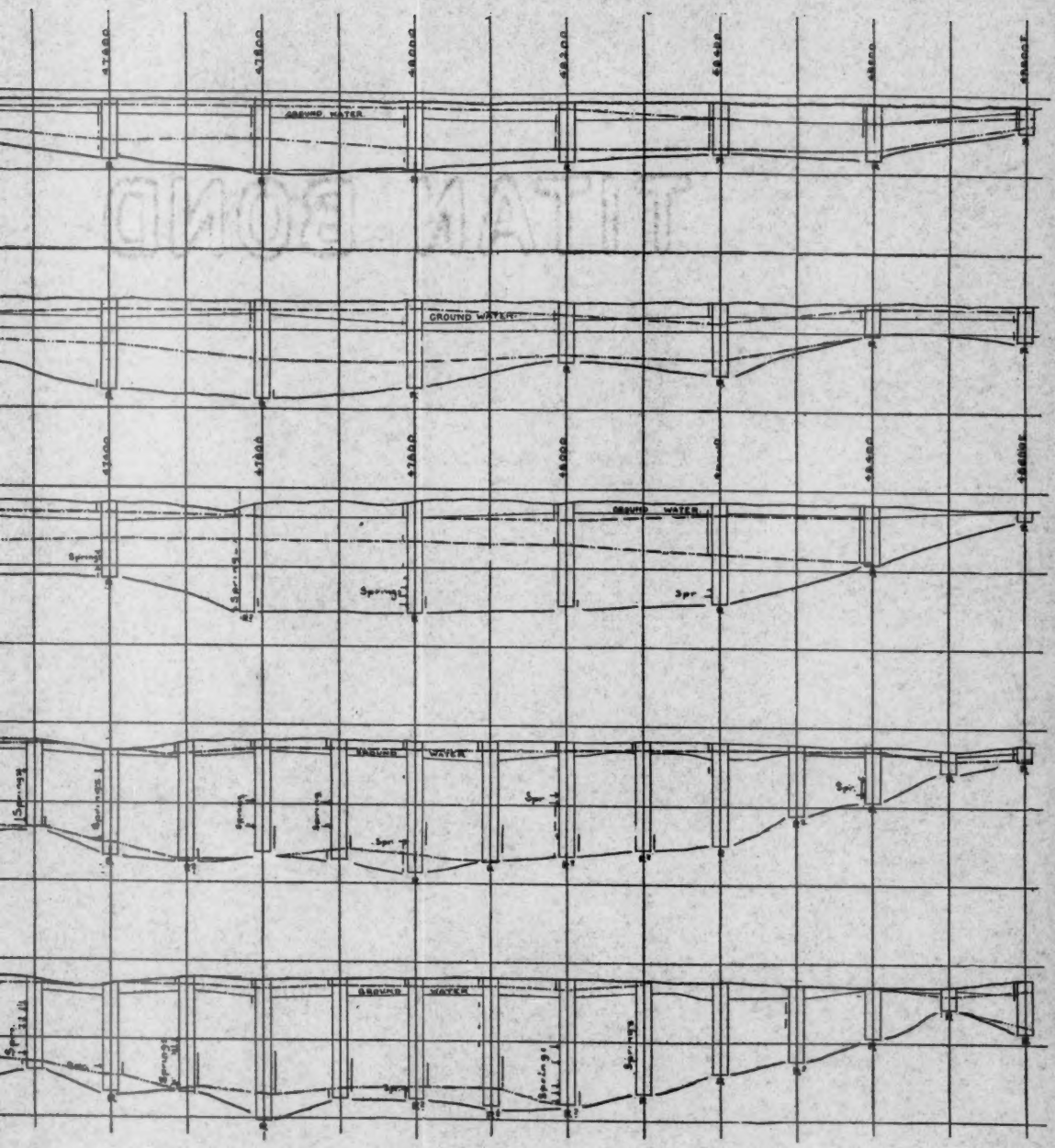
FIG. 12.—SELECTED EAST-WEST PROFILES BASED ON BORINGS IN THE WESTERL

Vertical lines on the left of the individual borings indicate partial or complete loss of on the right of the borings indicate, similarly, unoxidized material. Heavy vertical lines material. Of the horizontal lines, the upper full line represents the surface of the ground; mately) of the bed rock; and the intermediate full line, the surface of the ground water. T between the topsets and foresets; that broken by double dots, the boundary between the for dots, the boundary between the bottomsets and underlying gravel and ground moraine.



OFILES BASED ON BORINGS IN THE WESTERLY PORTION OF THE NORTH DIKE AREA.

al borings indicate partial or complete loss of water for the depths represented. Vertical lines ly, unoxidized material. Heavy vertical lines in the axes of the borings represent hard-packed full line represents the surface of the ground; the lower full line, the surface (at least approxi- e full line, the surface of the ground water. The line broken by single dots marks the boundary n by double dots, the boundary between the foresets and bottomsets; and that broken by triple nd underlying gravel and ground moraine.


GROUND WATER
GROUND WATER
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Springs
Springs
Springs

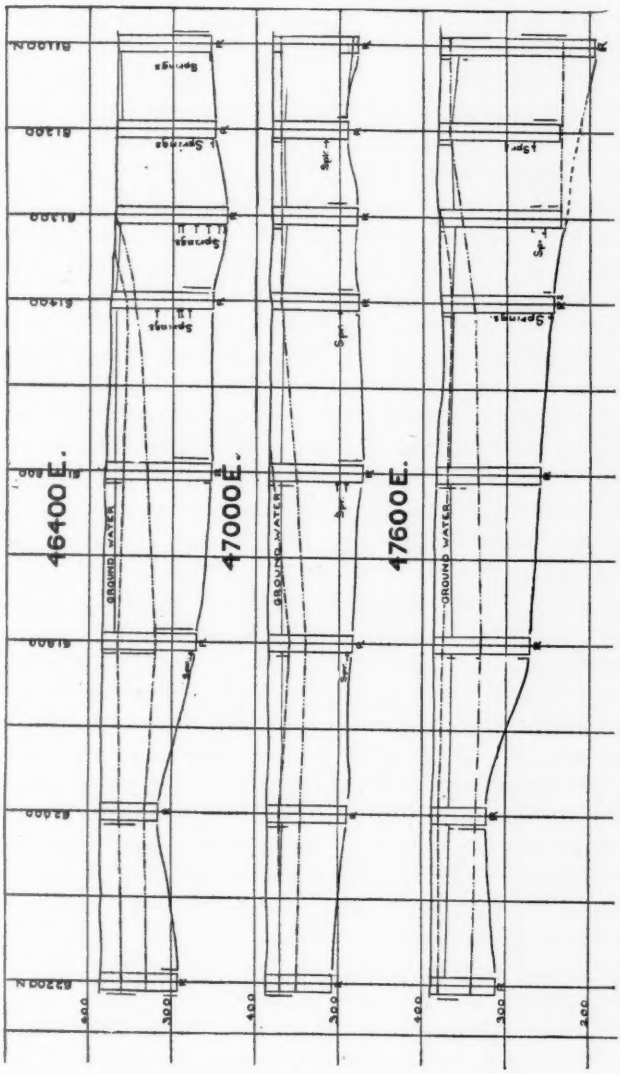


FIG. 13.—SELECTED NORTH-SOUTH PROFILES BASED ON THE BORINGS IN THE WESTERLY PORTION OF THE NORTH DIKE AREA.

Explanation the same as for Figure 12.

profiles (Figure 14) clearly show, where the till-clad slope of the Burdette Hill drumloid passes beneath the North Dike plain on the east, the mantle of till becomes rapidly thinner and dies out within a short distance from the margin, the till failing to cross reference line 53,400; but across practically the entire breadth of the complex valley to the cemetery ridge, a distance of more than 3,000 feet, the boring samples show on most of the profiles not a trace of till, and never more than one or two isolated thin patches. The only thing really suggestive of till in this part of the field is a basal layer of gravel, of obviously local origin, and ranging from a few inches to several feet in thickness, which many of the borings show resting upon the bed-rock surface. This basal gravel, varying from coarse to fine, but undoubtedly including much coarser material than the wash-drill samples indicate, might perhaps be interpreted as a washed till; but if so, the washing has been singularly thorough, for the samples show it to be entirely devoid of clay and rock flour; and there is no apparent reason why it should be differentiated in origin from the rest of the modified and water-laid drift. West of the cemetery ridge the facts are essentially similar for the northern profiles, the till being restricted to a few thin patches rarely exceeding 5 feet in thickness. But southward, down the sloping bed-rock plain, the till increases somewhat; and in the two or three most southerly profiles it is practically continuous, and varies in thickness from 2 to 30 feet.

This basal relation of the modified drift is, after all, not unique nor very unusual. On the contrary, it may be regarded as distinctly normal; for in my experience, as probably in that of most students of glacial geology, it is the exceptional case where the modified drift of narrow or well-defined valleys overlies continuously any important thickness of till. The superposition of modified drift (washed and stratified or water-laid sand and gravel) upon the ground moraine or till may occur to a limited extent on uplands and very generally on plains, either upland or lowland; but it clearly is not a normal feature of the drift deposits of definite or deep valleys. In other words, leaving plain tracts out of account, it may be said that till is as generally confined to hills and ridges as modified drift is to valleys;[1] and this suggests, by way of explanation, the further generalization that the basal currents of the ice sheet, at least in regions of strong and rugged

[1] Technology Quarterly, 9, 130.

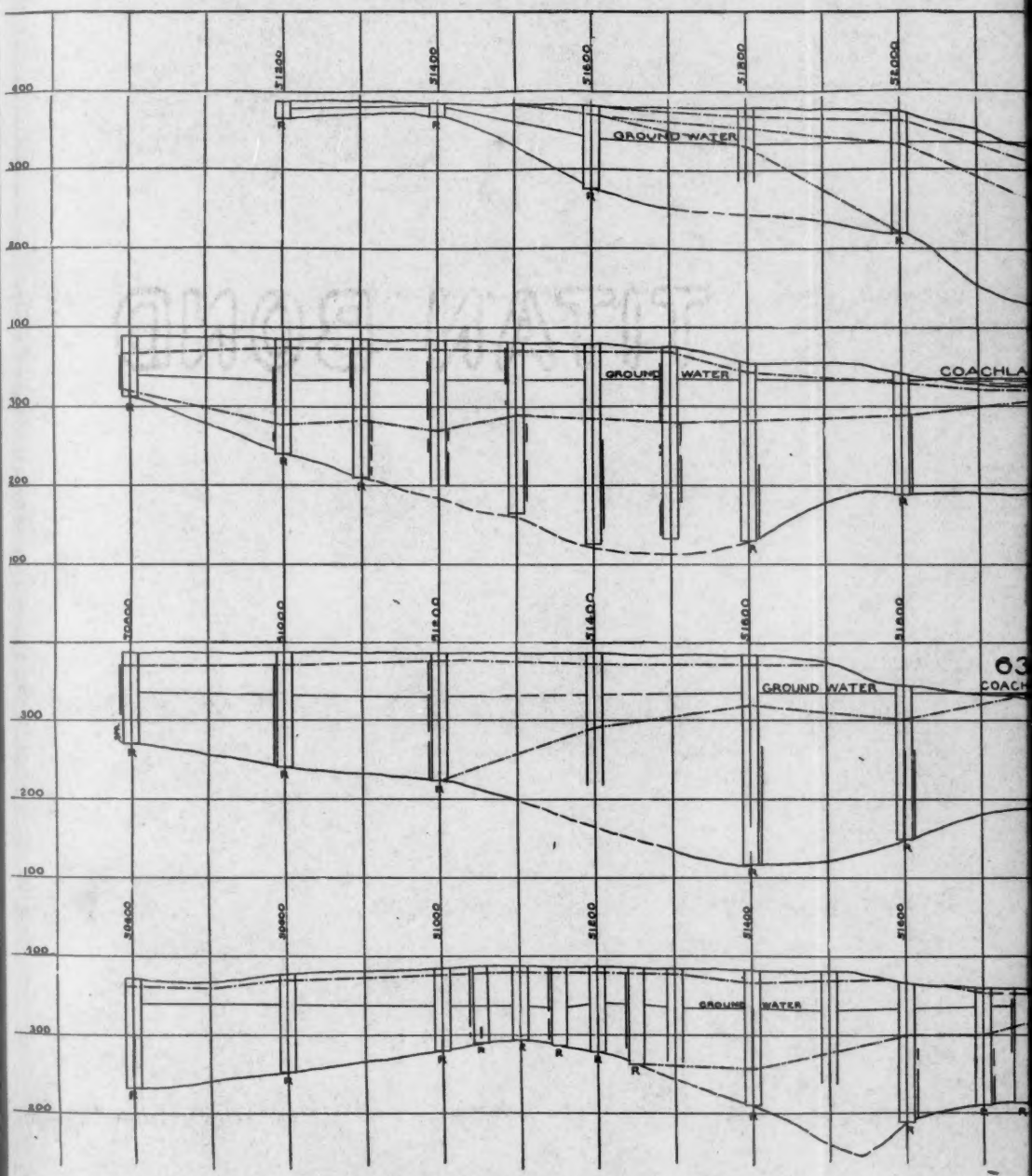
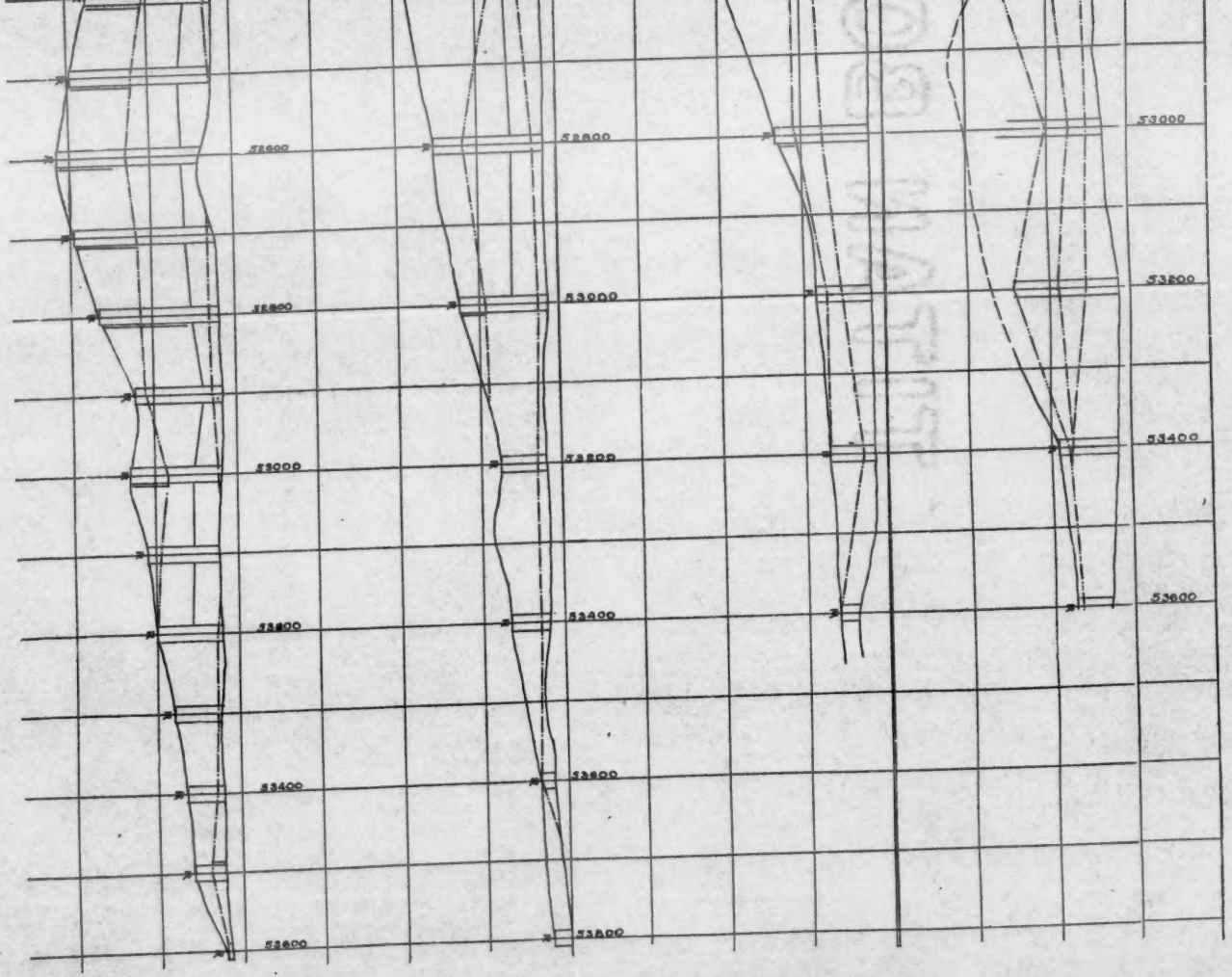


FIG. 14.—SELECTED EAST-WEST PROFILES BASED ON THE BORINGS IN THE EASTERLY PORTION OF THE NORTH DIKE AREA.

Explanation the same as for Figure 12.

64600 N
COACHLACE POND
64000 N
COACHLACE POND
63600 N
COACHLACE POND
63200 N
COACHLACE POND


53000
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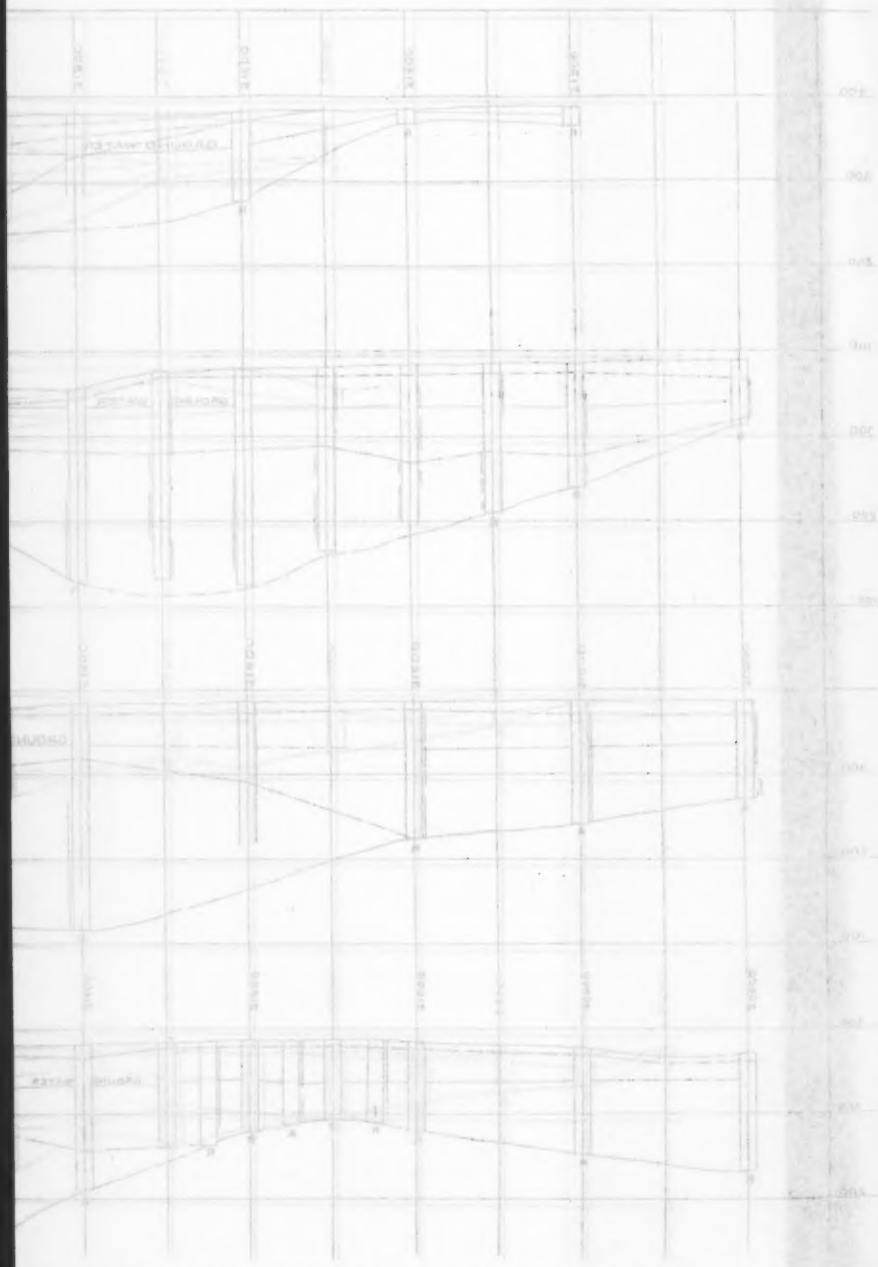

relief, were at the last concentrated in the valleys; and that, after the manner of Alpine glaciers and valley glaciers generally, they swept their channels clear of the ground moraine, the movement of the ice becoming more differential and localized as the thickness of the ice sheet was reduced by ablation, and continuing after the deposition of the main part or the whole of the ground moraine by basal melting. It may further be suggested that we have here, in the persistent movement of the ice and the dearth of ground moraine, a cause of the general non-occurrence of eskers in the axial portions of valleys, which may be regarded as supplementing the explanation previously proposed by the writer,[1] and based upon the tendency of the differential flow of the ice to determine lines of superglacial drainage along the sides of the valleys.

Collection and Classification of the Boring Samples. — The borings in the North Dike area were made with the wash drill (Figure 15), which consists essentially of a strong casing pipe approximately 3 inches in diameter, and the drill proper or water pipe about $1\frac{1}{4}$ inches in diameter, and terminating at the lower end in a cutting edge with two small holes for the escape of the water. The casing is driven into the ground by a cast-iron weight which encircles its uppermost length or drive head, and, falling freely, strikes on a collar firmly attached to the lower end of the drive head. In this collar is the outlet for the water which, escaping from the lower end of the drill, rises in the annular space between the drill and casing, and brings up, if the head of water be sufficient, all material loosened by the action of the drill, except pebbles and stones too large for the channel, or exceeding about 1 inch in diameter. Larger stones are either displaced or broken by the drill or casing. The outflowing stream of turbid water discharges into a tub in which the coarser materials in suspension settle, while the clay and rock flour are largely washed away with the overflow. At convenient intervals, and especially when a change in the character of the discharge is noted, the water in the tub is poured off, a sample taken from the accumulated sediment, and the tub cleaned out preparatory to the collection of the next sample. In absorptive strata a part of the water may escape into the ground, reducing the velocity of the excurrent stream sufficiently so that only the finer detritus is brought up; or the water may be wholly lost and no sample obtained

[1] "Origin of Eskers," *Proc. Boston Soc. Nat. Hist.*, 30, 382–404.

until the ground becomes saturated or the casing is driven deep enough to cut off the thirsty stratum. It has been found also that when the casing has reached the great body of fine sand and rock flour of which the lower part of the deposit is chiefly composed, the drill may be run down below the casing 100 or even 150 feet, the water rising for this distance in an uncased well of its own making without collapse or serious caving of the walls. Of course any enlargement of this unpro-

FIG. 15.—THE WASH DRILL IN OPERATION ON THE NORTH DIKE PLAIN.

tected part of the hole must diminish the velocity of the water through it, and thus, as in the case of "lost water," tend to prevent coarse sand or gravel from coming up, and make the samples more or less incomplete.

The majority of the samples were necessarily taken under the general conditions described above; and these are designated as regular or "incomplete" samples. These were supplemented for certain borings by special or "complete" samples, taken by holding a two-quart glass jar under the discharge and allowing it to fill but not overflow,

and then after the material in suspension had settled drawing off the water with a siphon. In cases of persistent turbidity (suspended clay) a few drops of hydrochloric acid were added to the water to curdle the clay, and thus secure a more prompt and perfect separation. With these precautions the special samples cannot fail to show in due proportion all the materials brought up by the water; but they are still likely to be imperfectly representative of the deposit as it exists in the ground when the detritus is coarse, or of a composite (coarse and fine) character, or where any important part of the water is lost. The special samples were taken at regular intervals of 5 feet, and an extra sample whenever a change in the character of the discharge was noted, thus making sure that no important changes were overlooked.

The special samples, with the regular samples from the same borings, were submitted to elaborate mechanical analyses and filtration tests to be described later; but the regular samples as a whole were far too numerous, as well as too incomplete in character, to justify anything more than a careful macroscopic examination with a view to an approximate classification in accordance with the following scheme: —

1. Coarse gravel.
2. Fine gravel.
3. Coarse sand.
4. Medium sand.
5. Fine sand.
6. Superfine sand.
7. Rock flour.
8. Superfine rock flour.
9. Clay.
10. Bowlder clay.

The coarser, and also the finer, grades are, as usual, highly composite or have high uniformity coefficients; while the intermediate grades, and especially 5, have, for reasons to be discussed later, a high degree of uniformity or relatively low coefficients. The *uniformity coefficient* is defined as the ratio of that size of grain than which 60 per cent. is finer to that size than which 10 per cent. is finer, this ratio varying inversely as the actual uniformity. A large number of determinations gave the following as the average or normal maximum sizes of grain in the four grades between medium sand and clay: 5 = 0.45 millimeter; 6 = 0.28 millimeter; 7 = 0.16 millimeter; 8 = 0.08 millimeter. The averages of the uniformity coefficients for these grades are as follows: 5 = 1.96; 6 = 2.11; 7 = 2.25; 8 = 1.53. These values of the uniformity coefficients are believed to be essentially normal for grades 5, 6, and 7, and technically so for grade 8. The values for grades 7 and 8 (2.25 and 1.53) are, in each case, the average of thirty-eight determinations, with minimum and maximum values of

1.49 and 3.30 for grade 7 and 1.15 and 1.88 for grade 8. But it is very difficult or practically impossible to accurately measure the finer particles of grade 8, since they are in their minuteness on the border line of clay; and it is very obvious that where falling below the technical effective size (the size than which 10 per cent. is finer) or even where aggregating less than 10 per cent. of the whole, they may still be regarded as an important factor in determining the real uniformity as well as in their influence upon porosity and percolation.

Many samples were readily recognized as intermediate, in the size of their dominant constituent, between the regular grades, and are accordingly designated by fractional numbers, as $6\frac{1}{2}$, $7\frac{1}{2}$, etc. Also many samples are visibly composite, and the designating numbers express the grades of the chief components. Thus 56 stands for a sample in which fine and superfine sand are the distinctive or prominent constituents, and so on.

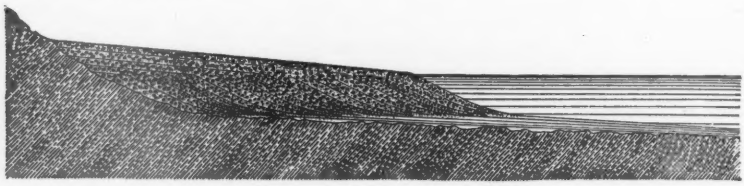

FIG. 16.—DIAGRAMMATIC SECTION OF A TYPICAL DELTA, SHOWING TOPSETS, FORESETS AND BOTTOMSETS. (Gilbert.)

General Structure.—A normal delta built by a swift and turbid stream in a body of standing water, that is, formed under the conditions existing in a glacial lake, embraces, as shown in the accompanying diagram (Figure 16), three approximately horizontal beds, which Davis has fitly named the topsets, foresets, and bottomsets. In the topsets, composed mainly of coarse material (gravel and coarse sand, grades 1, 2, 3) stranded on the upper surface of the delta, and in the bottomsets, embracing chiefly the finest silt (rock flour and clay, grades 7, 8, 9) deposited in the standing water beyond the outer margin of the delta and subsequently covered, at least in part, by the continued extension of the latter, the growth is principally in the vertical direction and the lamination horizontal; while in the foresets, formed on the growing edge or frontal slope of the delta and made up almost exclusively of material of intermediate textures (medium and fine sands, grades 4, 5, 6), the growth is horizontal and the lamination oblique, the laminæ sloping downward in the direction of growth.

The topsets, formed on a surface already aggraded nearly to the base level, are, in spite of their coarseness, of relatively slight aggregate thickness, and they are likely to be much thinner than the combined foresets and bottomsets, this ratio varying directly as the depth of the basin in which the delta is built. It would perhaps appear to many a natural if not a necessary assumption that the bottomsets also should be relatively thin, the foresets appearing thus as the dominant feature of the delta section. The relative thickness of the bottomsets must, obviously, tend to vary directly as the proportion of silt in the detritus delivered at the head of the delta by the tributary stream, and inversely as the area of the basin beyond the frontal slope of the delta; and it is clear that the thickness of the bottomsets should increase from the head of the delta outward because of the increasing time and diminishing area of deposition. Although these principles may require some modification as applied to ordinary deltas, marine and lacustrine, they are believed to be especially applicable to the deltas of glacial lakes of limited area, largely because of their relatively rapid construction and the consequent sharp delimitation of the component features.

The well-determined high proportion of silt (rock flour and clay) in normal drift, averaging more than 50 per cent. of the whole,[1] suggests for the limited basins of many glacial lakes an exceptional thickness of the bottomsets, especially toward the lee sides of the basins. The full thickness of the bottomsets is rarely disclosed in actual sections of important deposits; but even this fact added to the foregoing considerations fails to suggest the great depth of the bottomsets indicated by the numerous borings in the North Dike segment of the plain formed in true delta fashion during the Clinton stage of glacial Lake Nashua.

The borings do not, as a rule, reveal the attitude or dip of the lamination, even when adjacent borings are closely compared; and general conclusions as to the relative thickness of foresets and bottomsets must rest largely upon the assumption that grades 4 and 5 belong especially to the foresets, and grades 7 and 8 to the bottomsets, and that grade 6 holds an intermediate position, marking the transition from the foresets to the bottomsets. These assumptions were sustained by observation wherever, in the course of the engineering operations, the deltas have been sectioned. The most important opportunity for

[1] *Proc. Boston Soc. Nat. History*, **25**, pp. 115–140.

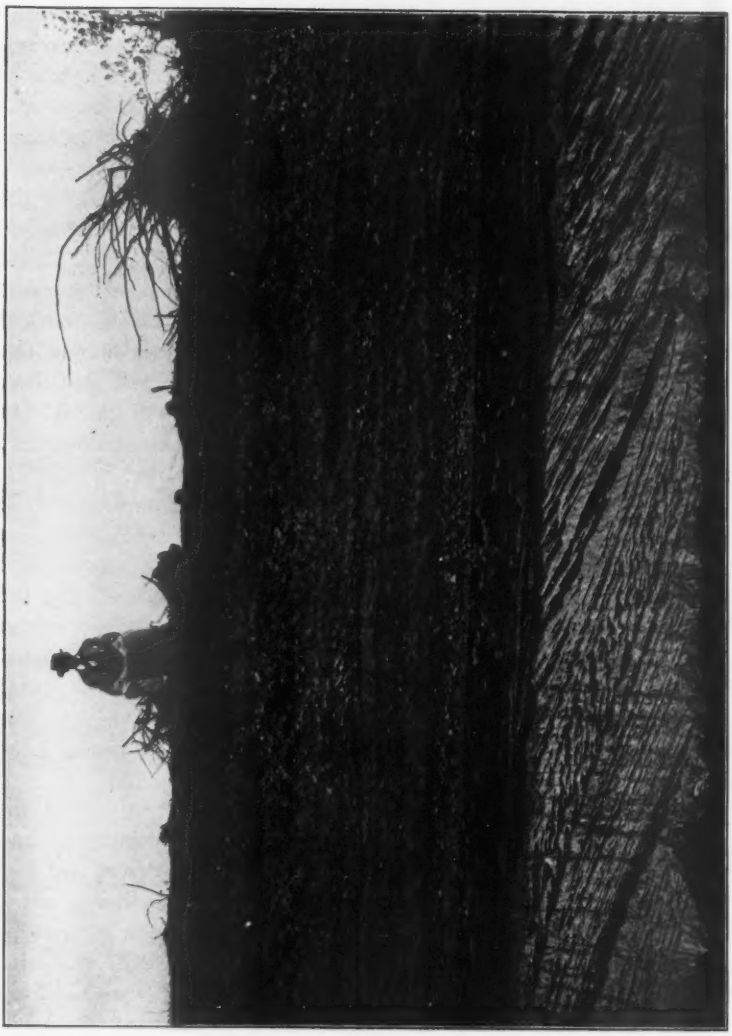

FIG. 17.—VIEW IN THE CUT-OFF TRENCH, SHOWING THE RELATIONS OF THE TOPSETS AND FORESETS. The dark material at the bottom is loam used in filling the trench, the entire depth of the foresets not being shown.

direct observation of the deposits below the surface was afforded temporarily during the construction of the North Dike by the primary and secondary cut-off trenches, the former extending the entire length of the dike, as indicated by the heavy line on the contour map and on the boring plans (Figures 10 and 11), and ranging most of the way from 30 to a maximum of 60 feet in depth. Notwithstanding that the trend of the cut-off is at most points transverse to the direction of delta growth, the walls of the great trench showed in general, below the coarse gravel of the horizontal topsets, rarely more than 10 to 15 feet thick, southward sloping layers of medium to superfine sand. One of the clearest exhibitions of the foresets in their normal relations to the topsets was that shown in Figure 17. Since the main purpose of the cut-off is to intercept the relatively pervious topset and foreset beds, it nowhere penetrates deeply the underlying and highly impervious bottomset strata; and hence these have nowhere been exposed for more than a small fraction of their thickness.

A careful comparative study of the borings, with the aid of the numerous north-south and east-west profiles, makes it clear that while the general direction of growth of the complex delta was southward, the foresets thinning and the bottomsets thickening in that direction, the section lying between Coachlace Pond and the cemetery ridges was developed chiefly in an easterly direction toward and finally against the lobe or block of ice, the subsequent melting of which developed the southern extension of the basin of Coachlace Pond, and which was continuous southward with the larger body of ice occupying and determining the site of Sandy Pond. Between the Sandy Pond ice block and the still larger but closely adjacent residuary mass of ice occupying the lower valley of Cunningham Brook was developed the narrow and almost esker-like ridge or isthmus of the delta plain, of which a section is shown in Figure 18. The anticlinal structure which the section exhibits is clearly due to the slumping of the material on the melting of the ice.

To summarize, the north-south profiles of the westerly portion of the North Dike plain reveal a normal delta structure, with the bottomsets rising to the southward and both the bottomsets and foresets becoming, on the average, of finer texture in that direction. East of the cemetery ridges, but heading against the same ice contact on the north, the growth of the delta was similar, but chiefly easterly to a lateral ice contact along the western borders of Coachlace and Sandy

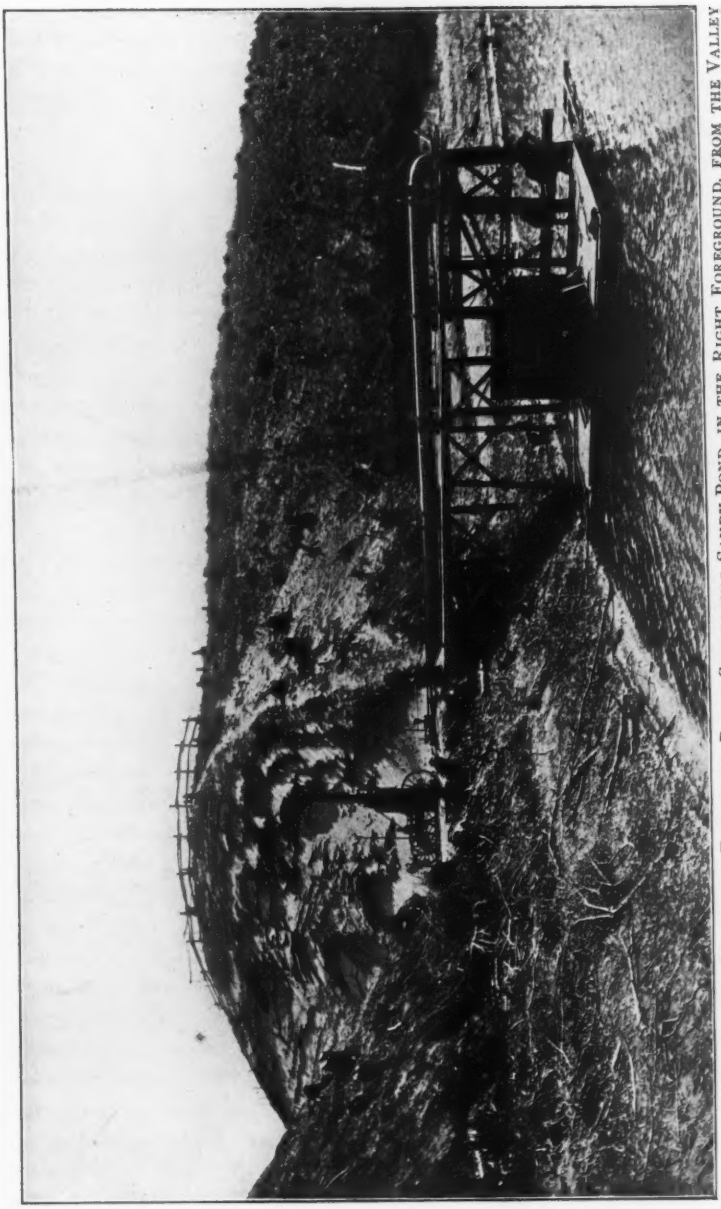

FIG. 18.—SHOWING A SECTION OF THE ESKER-LIKE RIDGE SEPARATING SANDY POND, IN THE RIGHT FOREGROUND, FROM THE VALLEY OF CUNNINGHAM BROOK.

Ponds. East of the ponds the development was again normal, from a head ice contact on the north and with a lateral ice contact on the west. In this case it may be noted in addition that the profiles cross the head contact, and thus give in that direction coarser material and more complete sections than for the westerly profiles.

Perhaps the best view to take of the relations of Sandy Pond to the plain is that its basin is not only a kettle hole, but that its north shore, continued eastward in a slightly marked but very obvious foss characterized by coarse gravel, is a subordinate ice contact against which was built especially that part of the plain lying south and east of the pond. This view helps us to understand the considerable thickness of coarse material underlying and blending with the normal bottomsets north and northwest of the pond.

The low uniformity coefficient and consequent high porosity of the more characteristic material of the foresets seems to find a ready explanation in the obvious principle, that, of the material swept by the distributaries of the glacial stream beyond the outer edge of the delta, only particles of a limited range in size could settle on any narrow zone of the frontal or foreset slope; and yet it is easy to see that the material would tend to become finer toward the bottom of the slope. In the standing water beyond the frontal slope the residuum of detritus in suspension must all settle eventually, with little or no assorting, where the process is continuous, the resulting deposit becoming thus highly composite. The importance of this principle in its relations to the storage and movement of the ground water in the sand plains of the glaciated area is obvious.

The theory of the formation of delta plains in glacial lakes requires that the recession of the stagnant margin of the ice sheet should be intermittent or characterized by more or less prolonged halts with, in general, a rather rapid recession from one halting place to the next. The essentially stagnant condition of the ice margin is proved by the rather rare distortion of the delta deposits due to a readvance of the ice. The glacial streams, superglacial and subglacial, tend constantly to build deltas in the standing water of the lake, but the normal form and structure are fully realized only where the ice margin recedes slowly enough to allow the deposit to be built up to the surface of the water. In other words, the determining factors are rate of recession, rate of deposition, and depth of water; and assuming deposition as constant, the formation of a delta demands, in general, that the rate of recession

shall vary inversely as the depth of the water, or at least that the rate shall be low when the water is deep, and practically zero for such exceptional depths of water as obtained in the North Dike area during the Clinton stage of Lake Nashua. In seeking an explanation of the intermittent retreat and prolonged halts of the ice margin, we naturally recognize climatic oscillations as probably an important if not a principal factor. I venture the suggestion, however, that we may find a still more potent cause in the accumulation on marginal portions of the ice, as now on the peripheral tracts of the Malaspina Glacier, of englacial drift which has become superglacial through ablation. Such a covering of drift must retard the melting of the ice, save, perhaps, where the contours of the latter favor the occurrence of standing or stagnant water. The condition here postulated appears, also, very favorable to the rapid building of an extended delta against the ice margin, since it affords an abundance of material in the most advantageous relation, especially if we assume superglacial streams as the chief active agency, as apparently we must with water from 100 to nearly 300 feet deep.

During the recession of the ice margin from the head of one delta to the head of the next delta of the series, the detrital tribute of the stream must be spread over the intervening tract as an imperfectly assorted and stratified and more or less tumultuous deposit of prevailingly coarse material, passing upward somewhat abruptly into the fine silts of the normal bottomsets. Thus we find a ready and adequate explanation of the varying thickness of gravel and coarse sand which many of the borings show between the bottomsets and the bed rock. The only wonder is that this record of a shifting ice margin is not more continuous. The observed facts and the natural tendencies seem, however, to leave us no alternative but to accept these basal accumulations as a normal feature of glacial deltas, a feature, too, which in its relations to the ground water must, notwithstanding its lack of continuity, be somewhat comparable with the foresets.

Kettles. — Associated with the North Dike plain are two distinct linear groups of kettles, or ice-block depressions. First, the east-west series characterizing the main ice contact, or northern margin of the plain. These are mainly small, entirely normal in all their relations, and demand no farther consideration, except to note that they are chiefly confined to the western half of this margin, west and south of Coachlace Pond, where the bed-rock elevations are greatest, while across the deep buried valley of the Nashua River they are wanting. Second,

the approximately meridional and closely connected series dividing the eastern half of the plain and including, as the map shows, the linear depression occupied by the southern lobe, or tongue, of Coachlace Pond, and the basin of Sandy Pond with the smaller kettle ponds trailing away from it in a southwesterly direction.

The kettles of the second series are, apart from their great disparity in size and the abnormal trend of the group, of special interest, because they closely follow the buried gorge of the Nashua, being developed in part, at least, over the lowest bed-rock contours, and because they are floored by exceptional thicknesses of modified drift. With the second series, also, may be correlated the large, isolated kettles, elongated in a north-south direction, formerly existing in the part of the plain crossed by the North Dike, one to the west and one to the east of Coachlace Pond, and one near the eastern edge of the plain, along the western base of Moffette Hill. These three kettles alone, besides the basin of Coachlace Pond, have been fully developed by the borings, and are crossed by the boring profiles. For these depressions, however, the data are full enough to encourage the hope that we may be able to determine their structural relations to the delta and the essential conditions of their formation.

The north-south trough of Coachlace Pond formerly connecting the main basin of this pond on the north with the basin of Sandy Pond on the south, but now mainly obliterated by the North Dike, was clearly neither an erosion trough nor a true foss, and hence it must be regarded as an elongated kettle. It is 2,000 feet long (see plan, Figure 11, and contour maps), 150 to 600 feet wide on the water line (elevation 334), and 50 to 55 feet deep, and the elevation of its flat bottom varies only from 325 to 330 feet. Figure 19 is a good general view of this depression in the North Dike plain, after it had been drained, looking in a northwesterly direction from the point where the great cut-off trench cuts its eastern wall. The opposing slopes are somewhat dissimilar ice contacts. As the photographic view (Figure 19) shows, the eastern slope is simple, meeting the upper surface of the delta and the flat bottom of the pond in sharply defined angles, while the western slope is more rounding and lobate, bearing some resemblance to a free delta front.

The samples from the numerous borings in and around this trough show (see the profiles, Figure 14) that, except toward the north end, where we approach the head of the delta and the main ice contact, its

FIG. 19.—VIEW OF THE BASIN OF COACHLACE POND, AFTER DRAINING, LOOKING NORTHWESTERLY FROM THE SOUTH SIDE OF THE MAIN CUT-OFF TRENCH, AND SHOWING THE RELATIONS OF THE STRATIFICATION OF THE NORTH DIKE PLAIN TO THE EASTERN SLOPE OF THE BASIN.

floor consists of the normal bottomset materials — superfine sand and flour (grades 6 to 8), and that these fine silts are essentially continuous downward to bed rock, 120 to 130 feet below. Also, we discover that the top or upper surface of this thick bed of bottomsets extends outward under the bordering plain at approximately the same level, with, in general, no indication of a slope toward the great kettle. Above this level, however, we find, as a rule, only the normal foreset materials, chiefly medium and fine sands (grades 4 and 5) overlain by a moderate thickness (5 to 20 feet) of coarse topset beds (grades 1 to 3).

Recognizing this trough as clearly due to the melting of a buried block of ice, the main question is as to the depth or horizon of its burial. The entire absence in most of the borings penetrating the floor of this trough of foreset or topset beds, and the absence, also, of any evidence that the strata are depressed toward the axis of the trough, tell strongly against a bed-rock position; and I see no escape from the conclusion that the depression is due to the melting of a block of clear ice at least 50 feet thick which rested on the impalpable bottomsets at about elevation 325, while it became enclosed by the advancing foresets. That the ice block rose above the surface of the water and thus escaped complete burial seems to be proved by the general absence of topset detritus on the floor of this trough. The horizontal bedding of the enclosing sediments was displayed with beautiful distinctness in the sides of the cut-off trench (Figure 19).

It is probable that on the melting of a deeply buried ice block the overlying sediments may yield or follow down by either slip or flexure, although in experiments the former result only was obtained. An adjustment by slipping involves farther adjustment by slumping until the normal kettle profile is developed. Figure 19 is, perhaps, as little suggestive of slumping as of flexing, for certainly we do not see at the bottom of the slope the volume of disorganized material that might be expected if the bank had slumped down from approximate verticality. It is possible, however, that this material has been subsequently leveled by water on the floor of the valley.

Accepting the view that this valley represents a block of ice resting on the bottomset sediments of Lake Nashua, it becomes an interesting question as to the probable origin of the block. Resting on or near the bed rock, it would have been easily explained as a residuary mass of the decaying ice sheet; but with 125 feet of impalpable stratified silt between it and the bed rock, this view becomes wholly untenable;

and thus there appears no escape from the conclusion that we have to do here with a stranded block or iceberg rather than a sedentary block, although it must be regarded as rather remarkable that so long a block should be thin enough to float in 50 feet of water. A third alternative, dispensing with the ice block altogether, is that this valley represents the failure of two distinct deltas to coalesce. The rounded and lobate western slope is much more favorable to this explanation than the straight and steep eastern slope. But for the fact that this trough terminates southward in the complete *cul-de-sac* of Sandy Pond, we might state, as a fourth alternative, the later erosion of a once continuous delta plain by the glacial stream. A stream capable of making such a channel must, however, have an outlet southward, or if flowing northward, an adequate source. In view of all these considerations, the most tenable hypothesis seems to be that of a stranded iceberg with continued growth of the delta from the westward but not from the eastward after the melting of the ice; and such a differential growth finds perhaps a sufficient explanation in the natural tendency of the ice to melt most rapidly on the western side.

The basin of Sandy Pond (contour maps and Figure 8, Vol. XVI, p. 252) is fully 60 feet deeper than that of Coachlace Pond, descending to elevation 268; and, as the map shows, the depth is far from being uniform. Again, the inadequate boring data suggest, if they do not fully prove, that it is underlain by coarse material; and hence there seems to be no reason why it should not be regarded as a normal kettle determined by a buried, residuary mass of ice. The still larger basin of the lower valley of Cunningham Brook, which, although not enclosed by the plain on the side toward the river, presents a superb ice-contact wall 80 feet high on the north, and is separated from the basin of Sandy Pond only by the narrow strip of the North Dike plain previously described (Figure 18), is a clearer case of a sedentary core of ice, since the granite and schist bed rock, with overlying bowlder clay, is actually exposed on its floor, while the Sandy Pond basin must cover, at least in part, the deep, preglacial gorge of the Nashua. In other words, these two contiguous basins so similar in outline and area are probably strongly contrasted in the depth of burial of their respective ice cores.

The kettle west of Coachlace Pond, lying directly north of the cemetery ridge and over a bed-rock valley tributary to the gorge of the Nashua (see contour map), is 1,050 feet long and about 300 feet in maximum breadth. It is somewhat composite, a major basin 45

feet deep being distinguishable from a minor basin on the north 25 feet deep. The elevation of the bottom at the lowest point is about 340 feet or distinctly above the level of the ground water, as determined by Coachlace Pond, 334 feet, and hence the kettle is dry. A well-marked depression connects it with the basin of Sandy Pond. The borings show depths of underlying gravel and sand varying from 62 to 130 feet, and corresponding bed-rock elevations of 235 to 288 feet; while a detailed study of the borings, with the aid of the profiles, shows practically a complete absence of bottomset sediments and a more or less distinct inward slope of the foresets and topsets. These facts point unequivocally to a sedentary ice block 50 feet or more in thickness, and that explanation is accepted for this case.

The large kettle in the thin eastern margin of the plain, where it meets the till slope of Burdette Hill (see contour map), was 1,200 feet long, 300 to 400 feet wide, and 10 to 30 feet deep, with from 10 to 40 feet of gravel and coarse sand between the lowest points of its transverse profiles and bed rock. Every profile shows the till of Burdette Hill thinning rapidly as it approaches this kettle and failing to cross its axis. All the conditions suggest the origin of the kettle in the partial or complete burial and subsequent melting of an elongated block or mass of ground or floe ice, and not of ice derived from the waning ice sheet. Since the bed-rock surface falls off toward the northern end of the kettle to elevation 315, it appears improbable that the core of ice rested on bed rock throughout, and all the facts are consistent with the supposition that the ice rested on a thick bed of gravel at all points.

Some 300 feet east of Coachlace Pond, on the line of the main cut-off of the North Dike, was the rather large, ill-defined and shallow kettle of which Figure 20 affords a good sectional view. The extreme depth was about 20 feet, and the boring profiles show 130 to 145 feet of underlying delta sediments, extending from elevation 356 down to bed rock at 226 feet, and including from the bottom up fully 100 feet of normal bottomsets (grades 6 to 8). The cut-off section (Figure 20) shows a very regular and unbroken downward flexure of the enclosing strata, and the facts indicate very plainly the origin of this kettle in the burial and subsequent melting of a rather large but relatively thin and thin-edged block of ice resting, as in the case of the Coachlace Pond block, on the upper surface of the bottomsets. How such a stranded block should fail to rise above the surface of the water in

FIG. 20.—VIEW OF THE BROAD, SHALLOW KETTLE EAST OF COACHLACE POND, LOOKING NORTH, AS IT APPEARED WHEN SECTIONED BY THE CUT-OFF TRENCH.

which it grounded is an interesting question. Among the answers that suggest themselves are ground ice formed during the long and severe glacial winter, and a stranded lens of ice which was by ablation reduced in thickness more rapidly than in area.

Between the last described kettle and Coachlace Pond the cut-off trench revealed in section the miniature buried kettle shown in Figure 21, and of which there was no indication in the surface features

FIG. 21.—A SMALL, BURIED KETTLE, FORMED IN THE FORESETS AND COVERED BY THE TOPSETS OF THE NORTH DIKE PLAIN, EAST OF COACHLACE POND, AS EXPOSED IN THE NORTH WALL OF THE CUT-OFF TRENCH.

of the plain. This is so clear a record of the contemporaneous burial and melting of a stranded ice block and obliteration of the resulting depression by continued sedimentation as to leave no room for argument. The finely laminated bottomsets and the coarse topsets are alike undisturbed, and it is plain that an ice block stranded on the former was overwhelmed by the foresets, which, although apparently horizontal, really slope downward toward the section, and then melted before the deposition of the coarse topset beds.

Summarizing this discussion, it is seen that the kettles of the North Dike plain are probably as diverse in origin as in form, and, conversely, it is interesting to note that pretty much all known or suggested conditions of kettle formation were realized almost simultaneously in this limited area.

Relations of the Water Table.—The North Dike plain is so completely interrupted by the cemetery ridges as to destroy the continuity of the water table, and in no respect is the contrast of the easterly and westerly portions of the plain more marked than in their relations to the level of the ground water. For the easterly portion this level is, of course, determined by the ponds, and it is interesting to note that before the conditions were disturbed by the construction of the North Dike the minor isolated kettle ponds were in substantial agreement as to water level with the Sandy-Coachlace basin. Above this level (about 334 feet) this part of the plain consists chiefly, and at most points wholly, of the foreset and topset beds, and the former especially are, in general, so highly pervious as to be without appreciable influence upon the water table, which is continued through them for long distances without sensible gradient or change of level. Where, however, the bottomsets, or sediments of finer textures and higher uniformity coefficients than grades 5 or 6, rise above the pond level, the water table promptly rises, attaining a maximum elevation of at least 365 feet, and a maximum gradient of 5 to 6 per cent. We must assume cross bedding of the foresets with alternating more and less pervious, sloping layers as a general fact, and observation shows that in spite of this the water table is a nearly level plane wherever it cuts this middle zone of the delta.

West of the cemetery ridges, where the North Dike plain has its most continuous and perfect development, the relations of the water table are distinctly different. Its normal level seems to be 365 to 370 feet, with an extreme range of 360 to 375 feet, and averaging 30 feet higher than the level of the ponds to the north and east. Although highest to the north and tending to sink with the plain to the south, the level is, in the main, remarkably uniform and parallel with the surface at depths of 10 to 20 feet. The ground water is virtually impounded by high land to the west, the cemetery ridges to the east, high bed rock to the north, and the rising and impervious bottomsets to the south. The latter barrier, especially, prevents the water from escaping freely through the valley of Cunningham Brook

to the Nashua River. The impounded or almost lake-like condition of the ground water affords but little opportunity to note the influence of the varying sediments upon the water level, especially since it is at nearly all points held well above the bottomset beds.

Lost Water. — We have noted that in porous and absorbent strata, especially above the level of the ground water, the water escaping from the drill may be partially or wholly absorbed and thus fail to return to the surface. This phenomenon, as we should expect, is well-nigh universal in the coarse and pervious topset and foreset beds above the level of the ground water. But it also often recurs at various depths down, perhaps to the bottoms of the deepest borings, and it is undoubtedly the most serious difficulty with which the drillmen have to contend, and frequently necessitates driving the casing in advance of the drill.

Below the water level the loss of water may be attributed, in many cases, to the simple difference of head, the water standing at a higher level in the drill or casing than in the ground, and thus tending to escape into the latter. But, as the boring profiles clearly show, the deeper strata in which the water runs away are usually interstratified with relatively or practically impervious beds of superfine sand and quartz flour, often of considerable thickness. We may usually suppose that the water escaping into such intercalated beds, however great the depth, simply causes an equivalent amount to overflow on the water table at the point, however remote, where the bed in question is intersected by that surface. In many cases, however, the avidity and completeness with which the water is absorbed suggest what may be called thirsty beds, that is, pervious strata enclosed by impervious material to such an extent as actually or virtually to isolate them from the free-moving ground water above, while in their downward extension they may connect with some body of coarse gravel, possibly pertaining to an earlier ice margin, having more or less free drainage at a lower level, and thus tending to deplete or exhaust the water of tributary beds. This hypothesis has been found requisite to explain some of the hard-packed sands encountered in the North Dike borings;[1] and as an explanation of the "lost water," it possesses the great advantage of not requiring the prompt movement of a long column of water through material in which the friction, added to the inertia of the water, would

[1] Technology Quarterly, 15, 260–264.

tend, by loss of head, to minimize the result. In other words, the thirsty sand is right at hand, and not at some remote point perhaps scores or hundreds of feet above the point of escape of the water. This explanation really postulates a localized water table, limited to a single stratum, and far below the normal level of the ground water; but that these conditions actually obtain we seem to have independent evidence in the "brown" or iron-stained sands to be described later, as well as in the hard-packed sands. The explanation might appear to accord best with the general fact that after a time the lost water returns; that is, ceases to run away. But for this phenomenon we have, perhaps, a simpler explanation in the natural tendency of the escaping water to close the interstices of the sand and thus prevent its own escape. Again, this explanation is in harmony with the fact that loss of water is unusual below the general drainage level of the Nashua Valley north of Clinton (elevation 200 to 250); and the apparent exceptions may, perhaps, best be explained as due to the continued escape of the water through some higher pervious stratum where the drill has gone below the casing, or even where it has not, since the water sometimes manifests a strong tendency to work its way up outside the casing.

It appears, then, that "lost water" may require, in different cases, three explanations: First, direct absorption by porous materials above the normal water table. This cause is nearly universal, though not always leading to a total loss, and it often operates more or less continuously from the surface of the ground to the level of the ground water. Second, indirect absorption by porous materials above the normal water table, through the medium of intercalated porous strata. Third, absorption by intercalated porous strata above a local low level of the ground water, determined by a relatively free drainage connection with a lower part of the valley.

Springs. — A common incident of the borings along the southern margin of the North Dike plain, especially in the westerly portion, where the development is more continuous and normal, and after the drill has penetrated the relatively impervious bottomsets, is a more or less vigorous artesian flow, the ground water rising from a foot or two to 10 or 15 feet above the surface. This phenomenon is known by the drillmen as a "spring." The artesian flow attains its maximum height above the surface when the boring is located in a kettle or other depression, and it never rises above the level of the head or northern edge

of the plain. This flow is entirely independent of the head of water used in operating the drill. It usually subsides, partially or completely, spontaneously within a few minutes, although it may continue unabated until the water-bearing stratum has been cut off by the casing. As the profiles show, this phenomenon may be repeated once or many times in the course of a deep boring. That the spring is a true artesian flow is unquestionable, for it is never observed while the drill is above the normal water table, and only when the boring intersects pervious strata intercalated in impervious sediments, the pervious strata being supposed to be, and in many cases proved to be, continuous to the surface.

As indicated, the relations of the springs to the structure of the North Dike delta are most fully and clearly exhibited in the westerly portion, the north-south profiles of which show (Figure 12) that the springs are strictly limited to the southern part of the plain; that they occur only in a thick and continuous series of bottomset strata; and that the elevations at which they occur increase to the southward with increasing elevation and depth of the bottomsets. In spite of their generally fine and impervious character, we must suppose that the bottomsets include some relatively pervious beds, which are, naturally, continuous upward and northward with still more pervious foreset beds. Southward these beds must become gradually finer and less pervious and die out as artesian horizons, and thus we find that the lower as well as the upper limits of the springs tend to rise to the southward.

Lost water and springs are terms denoting phenomena of distinctly opposite character, and for their interpretation we have in part assumed corresponding structural conditions, namely, limited pervious beds with free drainage in the case of lost water, and without free drainage in the case of springs. That these conditions actually exist may not be questioned, since they accord perfectly with the natural probabilities of the case, and since the two phenomena rarely concur even approximately, the springs occurring normally at lower levels in any given boring than loss of water, although the latter may now and then recur below the lowest spring, especially with borings of only moderate depth.

Even in borings in Coachlace Pond, water was frequently lost at depths of 25 to 100 feet, although the head of the water in the drill above the ground water in the bordering plain must be little or nothing. This seems to prove quite conclusively that the water is absorbed by thirsty or exhausted strata, and does not rise in saturated strata to overflow on the water table.

Ferruginous or Brown Materials. — In explaining the phenomena of lost water, especially at levels below the water table, we have assumed such a deep circulation of the ground water as would lead, at least periodically or during dry seasons, to the partial exhaustion of the water in certain more or less limited beds of sand and gravel intercalated with relatively impervious materials; and it was noted that the validity of that explanation is attested by other features of the deposits, including the brown and the hard-packed beds. The boring notes and samples proved the occurrence in the delta deposits, at varying depths and often far below the water table, of limited beds or streaks of iron-stained sand and gravel. The yellow to brown ferric hydrate, to which these materials owe their color and character, coats the grains and pebbles, and in some cases more or less completely fills the interstices of the sands and gravels. It is clearly a secondary feature, and the recency of its deposition is indicated by the strong ochery color which it imparts to the water. These ferruginous sands and gravels are clearly indistinguishable from the iron-stained and often more or less cemented materials frequently to be observed in superficial excavations, especially where closely underlain by an impervious stratum or floor of clay, bowlder clay, or bed rock. That they mark the courses of an intermittent subterranean drainage we cannot doubt. In its downward passage through surface mold and muck into the subsoil the ground water inevitably comes to hold in solution more or less ferrous carbonate, and when during the dry season the ground water largely drains away from these specially pervious strata and the diminished influx is, by virtue of its smaller volume, more highly charged with the iron salt, the latter is decomposed by the oxidizing action of the air, which must, of course, closely follow the water in its retreat, and the iron is deposited as the insoluble hydrate. The repetition of this process season after season leads eventually to the clogging of the stratum, and the slow dehydration and setting of the ferric hydrate to its cementation, and thus are developed the thin layers of ferruginous sandstone and conglomerate which the drillmen call hard pans.

In its general distribution and occurrence this phenomenon observes the same law as the lost water, that is, it is limited to relatively porous materials, occurs above the main water table, and also far below it, and its lower limit is approximately that of the lowest free drainage level of the region — the Nashua valley north of Clinton. This correlation is clearly not inconsistent with the fact that the water is often lost in

strata which are not distinctly ferruginous; for this character is rarely observed in thick beds, but belongs rather, as indicated by both observation and theory, to relatively thin beds or to the basal portions only of thicker strata. In many cases the ferruginous layers were so thin that they failed of representation in the boring sample, and there is good reason to believe that in many cases the drillmen failed to note their occurrence. But in spite of the fragmentary character of the evidence, the boring profiles clearly indicate the continuity of the ferruginous horizons from boring to boring as the normal fact. Since, however, the ferric hydrate is a secondary feature of the sediments, being still probably in process of formation, it is extremely unlikely that its development is uniform and continuous in any stratum, and certainly not in all. In other words, to the extent that the circulation of the ground water is localized or confined to more or less definite channels, the ferruginous sands and gravels must be patchy or lacking in continuity, and the frequent lack of agreement in this respect of adjacent borings is, therefore, entirely normal. Ferruginous sands and gravels, like loss of water, may occur at different depths in the same boring, showing that the phenomenon is not best explained by a simple vertical movement or percolation of the ground water, but demands a localized circulation in the bedding planes.

A comparative study of twenty-eight brown samples from five borings in the easterly portion of the North Dike plain shows a range in elevation from 202 to 355 feet, the average elevation being 295 feet and the normal elevation of the water table 334 feet. Although the brown material is, in several instances, a surface deposit, the depth of its lower surface below the top of the ground ranges from 13 to 183 feet, with an average of 71 feet, the maximum depth corresponding to the maximum elevation of the delta plain. The brown layers range in thickness from 2 to 55 feet, with an average of 14.5 feet. The majority, however, are under 10 feet; and it is altogether probable that the exceptionally thick beds at least are composite, embracing several or many ferruginous bands. The brown material is normally, or before it becomes clogged with iron oxide, of a coarse and highly pervious character, chiefly grades 2 to 6; and it goes without saying that it belongs, in the main, to the topset and foreset zones, rather seldom extending to the coarse beds intercalated in the bottomsets, since the latter are not usually free draining, tending to become more impervious downward or away from their connection with the overlying zones.

Of special significance and interest in this connection is the fact that, practically without exception, the enclosing strata are of a relatively fine and impervious character, confining and controlling the movement of the ground water in the coarser beds, and this relation holds almost absolutely for the underlying stratum. Brown material was encountered in several borings in Coachlace Pond, and in two instances the material is essentially superficial, with maximum depths of 15 and 16 feet. It is clear that these must antedate the building of the dam of the Bigelow Carpet Mills, to which this part of Coachlace Pond owes its existence.

As we might expect from the impounded and virtually stagnant condition of the ground water in the westerly portion of the North Dike plain, the ferruginous sands are more shallow and more restricted in their vertical range. The extremes of elevation are 285 and 375, with an average of 344 feet. The beds are even thinner than in the eastern group, but otherwise are subject to the same generalizations. In one instance the same 5-foot brown bed is traceable in a north-south direction through successive borings for 400 feet, descending in that distance from elevation 360 to 335, or 25 feet, with a concomitant increase in the fineness of the material from grade 5 to grade 6.

That the ferruginous horizons noted by the drillmen and represented by the samples are but a small fraction of the total number is distinctly indicated by the fact that in the few borings the sampling of which was closely supervised, we have proof of several or many successive sheets of ochre-impregnated sand and gravel, with a vertical sequence which could not be explained by a direct vertical penetration of the ground water, but demands an intermittent circulation along the bedding planes.

Buff or Oxidized Drift. — Besides the highly ferruginous yellow and brown materials, due to the impregnation of relatively thin intercalated or basal layers of porous sand and gravel by ferric hydrate through the agency of an intermittent flow of water, and the peroxidation during the dry season of the iron contained, chiefly as carbonate, in the residuum of the ground water, we must take account of the general contrast in color between the normal gray or bluish gray of the entirely unoxidized drift and the more or less distinct buff tint developed by oxidation in the main body of the drift above the water table, and, more generally, above the lowest limit to which the ground water may recede during periods of drought. While the buff tint is, doubtless, due in part to the peroxidation of the ferrous iron originally

contained in the sediments of the glacial lake, we may, perhaps, fairly assume that it is, in the main, but a thinner impregnation, due to the less ready and complete oxidation of ferrous carbonate introduced by the ground water and held by capillary attraction in a permanent and even dissemination, instead of becoming concentrated by a gravitative flow.

The absence of the buff or oxidation tint above the normal water table, or above the lowest limit of oxidation, is, of course, a reliable indication that the material is not readily permeable, and on this account the distribution of the blue or unoxidized material was carefully noted in all the borings and on the boring profiles. Generally speaking it is limited to grades finer than 6, and it is rather rarely wanting in grades finer than 7, being especially characteristic of the great thickness of grade 8 making up the bulk of the bottomsets. These generalizations hold almost regardless of the depth, grade 8 not being extensively oxidized, even above the water level, while grade 6 and coarser grades have rarely escaped oxidation, even at the greatest depths reached by the borings.

The facts are essentially the same for the westerly as for the easterly portion of the North Dike plain, although the conditions, at least as regards the structure of the deposits, are, for the former, specially unfavorable to a general or deep movement of the ground water. In fact, for corresponding materials and depths the oxidation is, if anything, more general than in the easterly portion of the plain; and this may, perhaps, be attributed to the fact that the rising of the bed rock to the northward virtually forces the proximal or head ends of all the strata into the region of or above the water table.

These facts indicate a general circulation of the ground water which is not definitely limited downward by the water table, and which, be it never so slow and feeble, carries with it the oxidizing influence of the atmosphere in the form of dissolved oxygen, for we cannot readily conceive the water as actually draining out of these sediments below the general drainage level of the valley, and certainly not below the level of 200 feet above tide. That the circulation is, as usual, horizontal, or with the bedding, is proved by the common occurrence of oxidized sands of various grades below considerable and continuous thicknesses of unoxidized quartz flour.

Hard-packed Sand and Gravel. — This topic has already been referred to as closely related to the phenomena of lost water and fer-

ruginous sand and gravel, and since the data afforded by the North Dike borings have been discussed in a previous paper,[1] an outline of the facts and the conclusions which they suggest will suffice here.

By the term "hard-packed" the drillmen mean that the drill penetrated the material slowly and with difficulty. Usually only one hard-packed layer was reported in each boring, but in a few instances as many as three or four. The hard-packed samples, although prevailingly coarse, vary in grade from coarse gravel to quartz flour, and a classification of eighty-seven samples resulted as follows: gravel, thirty-two; coarse and medium sand, thirty-two; fine sand, fourteen; superfine sand and rock flour, nine.

In three instances only is the surface layer described as hard-packed, and, generally speaking, the hard-packed material is found only well below the local water level and yet above the level of the Nashua River below Clinton, the practical limits of the vertical range being 330 and 240 feet above the sea, while the level of the river in the lower part of Clinton is 250 feet, and in Lancaster, two miles to the northward, 237 feet.

The hard-packed gravel and coarse sand are composed in large part of flat or scaly fragments of schist, mica, etc., which must have been deposited by the water in approximately parallel horizontal planes. This position, of course, offers the greatest resistance to the disturbance of the deposit by a force acting in the vertical direction, although it does not necessarily tend to prevent water from flowing through the formation freely in a horizontal direction. Practically, all the hard-packed samples above the level of the ground water and nearly all those below the level of the Nashua River belong to the coarse and scaly grades.

This explanation is inapplicable to the finer hard-packed samples, since they consist almost exclusively of quartz in angular and sub-angular grains, and it appears that with these finer grades of material especially the "hard-packed" condition depends chiefly upon the proportion of water which the material contains. To determine this point a series of experiments was made, from the results of which it is fair to conclude that the hard-packed condition is indicative of a high degree of porosity, or at least of a free movement of water through the deposit, and that either the material is scaly in form or it contains

[1] Technology Quarterly, 13, 260–264.

insufficient water to fill the pores, or these conditions co-exist. According to this explanation, the water supplied by the drill must tend to escape into the ground in hard-packed layers, and this has been commonly observed; but the real test of hard-packed sand or gravel is the fact that it resists the free impact of the drill, be the loss of water great or small.

A fact of special interest in connection with this topic is presented in the truly remarkable power of the finer silts, and especially the quartz flour, to maintain an open hole with a strong stream of water running upward through it, when the drill is 50 to 150 feet below the casing. The material itself in such cases is mainly unoxidized and entirely uncemented, and, under normal conditions, quite incapable of offering effective resistance to stream erosion. The best explanation of this phenomenon appears to be that the sand or flour is in a partially drained or semi-saturated condition, which makes it somewhat absorbent, and the tendency of the water to escape into the sand creates an outward pressure which holds the grains in place. Also, the condition of semi-saturation insures for the interstitial water the maximum development of surface tension, thus giving the water its greatest efficiency as a cement. Two principles thus coöperate to secure the stability of the drill hole: first, the surface tension of interstitial water, giving the deposit as a whole its firm and semi-solid character; and second, the outward pressure of the water on the surface of the semi-saturated but nearly impervious silt, which, under the condition of complete saturation or equalized pressure, would behave almost like quicksand.

Not infrequently the uncased holes have remained unclosed by caving during one to several days, and it may be noted that, during the operation of the drill in a hole, enlargement due to the erosive action of the outflowing stream of water must reduce the velocity of the stream and thus check its own ravages; but, on the other hand, with every increase in the size or radius of a hole, its arch becomes less and less self-sustaining.

With a view to determining the actual average diameter of borings made under these conditions, and also in some cases the distribution of the erosive action of the water, or its relative efficiency in materials of different character, the drill was allowed, in some cases, to discharge into a tank, from which the water was subsequently drained off and the accumulated silt measured. The dimensions of the tank were 8 by 10 feet, with the outlet 18 inches above the bottom, and it was

divided by vertical partial partitions in such a way as to give virtually a continuous channel 24 inches wide, 18 inches deep, and 40 feet long. The overflow from the tank was invariably free from marked turbidity. The volume of the silt divided by the corresponding depth of the boring afforded at once the average section and diameter of the latter. Thus in a boring reaching a total depth of 221.8 feet the casing was driven only to 83 feet, mainly through oxidized or buff material of grade 7, and below this the material was chiefly unoxidized or blue of grades 7 to 8. The material caught in the tank indicated for the 83 feet protected by the casing an average diameter of 5 inches, or nearly double the diameter of the casing, while for the unprotected lower part of the boring the average diameter was only 4 inches. In a second hole, with a total depth of 247 feet, the casing was driven to the bottom. The bottom of the oxidized zone was reached at 97 feet, and the contents of the tank indicated for this depth a hole 3.55 inches in average diameter, and for the remaining 150 feet in the blue bottomsets an average diameter of only 3.03 inches. In a third boring, 166 feet deep, the casing was driven to 59 feet, with an amount of material sufficient to account only for a hole 2.5 inches in diameter, and since the diameter of the casing is 2.75 inches we have indicated a lateral displacement of material equal to 10.15 linear feet, or 17.2 per cent. of the boring. Below the casing the average diameter was 2.6 inches, corresponding to a displacement of 10.5 per cent. Finally, in a boring 197 feet deep the casing was driven to the bottom, and the average diameter for the entire depth found to be 2.75 inches, or just that required by the casing.

It appears from these representative examples that, while the results are somewhat variable as regards the actual extent of erosion accomplished by the water from the drill, the erosion is likely to be less in the unoxidized and relatively impervious bottomsets than in the oxidized and relatively pervious foresets, even when the former are unprotected by the casing, and that in some instances where the drill has been run below the casing the hole does not exceed the minimum size required by the drill and its excurrent stream.

Mechanical Analyses and Filtration Tests.

The laboratory examination of the samples from the North Dike borings was confined to the special or complete samples from the borings on the line of the main cut-off, and, for purpose of comparison,

both the regular and special samples from a special group of ten deep borings on the west side of Coachlace Pond.

In the mechanical analyses or sizing experiments, 20 grams of the dried sample were passed through a graded series of sieves ranging from 4 to 170 mesh, and the amount caught on each sieve weighed. The sizing was carried farther for the material passing through the finest sieve by settling in still water. For this purpose 5 grams of the material, mixed with a small volume of water, were introduced into the top of a vertical 5-foot column of water contained in a glass tube of $\frac{1}{2}$ inch internal diameter, and the depths of material settling in five, fifteen, twenty-five, and sixty minutes measured and the corresponding percentages calculated. Material remaining in suspension at the end of sixty minutes was caught on a filter, dried, weighed, and reckoned as clay, although known by microscopic examination to consist largely of the finest grades of quartz flour. From the data thus obtained from each sample was plotted a curve from which were deduced the effective size and uniformity coefficient, as previously noted, and as a general result of special interest may be mentioned the absence, even in the superfine quartz flour (8), of mo e than a trace of true clay. In many cases where the drill foreman, judging by the turbidity test, reported clay, the analysis showed it to be wholly wanting.

The filtration tests were made in brass tubes having a cross-section equal to 1 ten-millionth of an acre, and long enough to receive a charge 6 inches in depth, and most of the tests were made with a 10-foot head of water. The material, thoroughly dried and mixed, was well packed by jarring and ramming, and the air exhausted by suction before the water was turned on. Experiment shows that the interstitial air of fine, dry sand may clog the sand against the downward passage of water almost as efficiently as clay would, and that water charged with air or well aërated will give up air to the sand. The best results, therefore, are obtained when recently boiled, distilled water is used and the temperature of the water is kept as nearly constant and normal as possible. In these tests the temperature of the water ranged from 65° to 70° F. When the water is turned on the rate of filtration, expressed in cubic centimeters per minute, usually shows at first a marked acceleration, owing to the solution by the water of the residual air, and in spite of the fact that the movement of the water through the sand naturally tends, by readjustment of the finer particles, to close the pores of the sand and check filtration. Hence the maximum and most normal rate

of filtration is reached, as a rule, only after several times its volume of water has passed through the sand.

The general filtration averages for the various simple grades and some of the simpler composite grades are given in the following table. The results represent two series of borings: first, those on the central line of the North Dike both east and west; and second, a group of ten borings in an area 600 by 800 feet on the west side of Coachlace Pond and crossed by the central line. The values for the central line borings represent special or complete samples only, while for the group of ten borings the values are also given for the corresponding regular or incomplete samples; the contrast being most marked, as we should expect, with the finer grades or those containing the largest proportion of impalpable material. The table also contrasts for the finer grades the filtration values for the oxidized and the unoxidized materials, the latter, as we should expect, being, as a rule, decidedly the lower. The table also affords abundant illustration of the principle that the composite are less readily permeable than the homogeneous grades, the filtration values varying inversely as the uniformity coefficient.

FILTRATION AVERAGES.

Expressed in cubic centimeters of water per hour through a column 6 inches long with a diameter of about 0.8 of an inch, equivalent to a cross section of 1 ten-millionth of an acre, and under a head of 10 feet.

	Grade.	Borings on Central Line.		Special Group of Ten Borings.			
		Number.	Average.	Special samples.		Regular samples.	
				Number.	Average.	Number.	Average.
Oxidized.	5	13	14,135	4	6,677	20	13,920
	5, 6	12	8,448	11	8,853	18	6,587
	5½	21	9,902	3	14,045	5	8,368
	5½, 6	28	4,678	. .	. .	. .	. .
	6	32	3,581	5	3,459	21	5,285
	6, 7	52	910	19	1,635	18	1,744
	6, 8	10	225	11	685	1	693
	6½	34	1,232	4	864	8	2,693
	6½, 7	20	821	. .	. .	. .	. .
	6½, 7½	24	255	. .	. .	. .	. .
	7	72	331	22	595	32	805
	7, 7½	57	194	. .	. .	. .	. .
	7, 8	75	108	13	133	4	400
	7½	71	135	22	91	3	827
	7½, 8	73	70	. .	. .	. .	. .
	8	49	23	5	29	1	227
Unoxidized.	7	14	130	3	373	5	267
	7, 7½	8	148	. .	. .	. .	. .
	7, 8	18	73	13	112	9	128
	7½	42	68	6	64	1	363
	7½, 8	41	46	1	85	. .	. .
	8	65	22	22	29	9	91

The use of the tank in connection with some of the borings of the special group afforded a means of obtaining general samples, which, although not accurately representing any material actually occurring in the ground, made possible a comprehensive comparison of the sediments in the shallow zone of the foresets and the relatively deep region of the bottomsets. Tank samples, if properly taken or truly representative, must in any case be of a highly composite character and give low filtration rates, but still a difference in this respect may be noted between the foreset and bottomset zones. Thus, for one of the special borings the tank samples gave from the surface to 83 feet a filtration rate of 28.7 cubic centimeters per hour, and from 83 feet to 221 feet the rate was only 10 cubic centimeters per hour. In another case, from the surface to 97 feet the rate was 18 cubic centimeters per hour, and from 97 feet to 247 feet, 13.8 cubic centimeters per hour. In a third case, from the surface to 59 feet the rate was 35 cubic centimeters, and from 59 to 166 feet it was less than one-fourth this amount, or 8.4 cubic centimeters per hour; and for a fourth boring the corresponding results were 12.4 cubic centimeters from the surface to 101 feet, and 8.4 cubic centimeters from 101 feet to 224 feet.

With a view to noting the influence of varying size and uniformity of grain upon the filtration rate, the following experiments were made: typical foreset and bottomset sediments were submitted to careful mechanical analysis in sufficient amounts to afford enough material of each size for several filtration charges. These fractions were then tested separately, with the results noted below. The mean size of grain is given for each fraction, as well as the mesh on which it was caught. For the coarser fractions especially the rate of filtration shows a notable increase in successive trials with the same charge, owing to the solution of the interstitial air, but the figures are given in full only for the first fraction, and it may be stated further that this result is to be clearly observed in any case only when readings are taken from the beginning of filtration. The rate of filtration is expressed in cubic centimeters per minute when not otherwise stated.

INFLUENCE OF SIZE AND UNIFORMITY OF GRAIN UPON FILTRATION RATE.

FRACTION 1. — Through 24, caught on 30, mean size, 0.500 mm.
First charge, 633, 731, and 740 c.c. in successive minutes.
Second charge, 785, 852, and 868 c.c. in successive minutes; after running ten minutes, 885 c.c. in one minute.

FRACTION 2. — Through 30, caught on 40, mean size, 0.427 mm.
First charge, average 586 c.c. per minute.
Second charge, average 554 c.c. per minute.

FRACTION 3. — Through 40, caught on 50, mean size, 0.350 mm.
First charge, average 372 c.c. per minute.
Second charge, average 373 c.c. per minute.

FRACTION 4. — Through 50, caught on 60, mean size, 0.277 mm.
First charge, average 225 c.c. per minute.
Second charge, average 244 c.c. per minute.

FRACTION 5. — Through 60, caught on 80, mean size, 0.205 mm.
First charge, average 148 c.c. per minute.
Second charge, average 141 c.c. per minute.

FRACTION 6. — Through 80, caught on 100, mean size, 0.137 mm.
First charge, average 75 c.c. in one minute.
Second charge, 75 c.c. in one minute, and then 755 c.c. in ten minutes.

FRACTION 7. — Through 100, caught on 120, mean size, 0.129 mm.
First charge, average 52 c.c. per minute.
Second charge, 52 c.c. in one minute, and then 518 c.c. in ten minutes.

FRACTION 8. — Through 120, caught on 140, mean size, 0.106 mm.
First charge, 33 c.c. in one minute.
Second charge, 331 c.c. in ten minutes.

FRACTION 9. — Through 140, caught on 170, mean size, 0.080 mm.
First charge, 220 c.c. in ten minutes.
Second charge, 224 c.c. in ten minutes.

FRACTION 10. — Finer than 170 mesh, composite.
35 c.c. in one hour.

FRACTION 11. — Finer than 170, settled in five minutes, mean size, 0.062 mm.
135 c.c. in one hour.

FRACTION 12. — Finer than 170, settled in ten minutes.
48 c.c. in one hour.

FRACTION 13. — Finer than 170, settled in twenty-four hours.
20 c.c. in one hour.

A LABORATORY STUDY OF THE STAGES IN THE REFINING OF COPPER.[1]

By H. O. HOFMAN, C. F. GREEN, and R. B. YERXA.

Introduction.

In refining copper, the metal is melted down in a reverberatory furnace in a more or less oxidizing atmosphere and then further subjected to an oxidizing smelting in order to eliminate the common impurities, most of which have a stronger affinity for oxygen than has copper. In these operations some of the copper is oxidized to cuprous oxide and dissolved by the metal bath. When the quantity of dissolved cuprous oxide has reached about 6 per cent., the metal is said to have been brought to "set-copper." A button-sample will show a depressed surface and, when broken, a single bubble at the apex of the depression; the fracture will be brick-red and dull. It is essential to carry the oxidation to this point in order to know that the impurities have been oxidized as far as it is possible under the given working conditions. Nearly all the cuprous oxide of the set-copper is now reduced to the metallic state by poling, when "tough-pitch" copper will be obtained. A button-sample will show a flat surface. Upon breaking, it will be found that the former bubble has disappeared and that the fracture has become rose-colored and shows a silky luster. The quantity of cuprous oxide allowed to remain in the copper will vary with the impurities still present in the metal, and with the degree of pitch that it is desired to reach. It is essential for the general physical and the mechanical properties of the resulting copper that such impurities as arsenic, antimony, bismuth,[2] and lead, when present, shall be in the

[1] Reprinted from *Transactions of the American Institute of Mining Engineers*, New York meeting, October, 1903.

[2] This generally accepted statement by Hampe (*Zeitschrift für Berg-, Hütten- und Salinen-Wesen in Preussen*, 1874, XXII, p. 121) is doubted by Roberts-Austen (*Journal of the Society of Chemical Industry*, 1894, XIII, p. 471), who, in discussing Gowland's paper, "A Japanese Pseudo-Speise (Shiromé)," etc., says, "However small the proportion of bismuth in copper might be, it always remained free, and did not unite with the copper."

oxidized state, as they are then less harmful than when present in the metallic state. Refiners commonly distinguish "ingot- or cake-pitch" and "wire-bar pitch"; copper brought to the former condition contains more cuprous oxide than the latter. These two pitches are, however, not absolutely fixed; they vary with the practice of the individual refiner and with the thickness of the cake or bar that is to be cast: the thicker the piece, the more oxygen will have to remain in the metal, if a flat surface is to be obtained. A third degree of pitch aimed at is that required by very thin castings, such as electrodes $\frac{1}{2}$ inch in thickness. As this pitch lies beyond that of wire-bar copper and differs from it more than will permit of its being designated as merely a shading, it may be called "plate-pitch."

Little was known of the structural relations that exist between copper and cuprous oxide until 1900, when Heyn[1] published the results of his investigations on "copper and oxygen." He took pure copper wire, cut it into small pieces, made up charges of 450 grams each, added to them varying quantities of pure cuprous oxide, melted the mixtures (excepting sample Number 1) in graphite crucibles lined with porcelain, inserted into the fused charges the protected couple of a Le Chatelier thermo-electric pyrometer, and made the cooling-curves. Sample Number 1, copper wire alone, was fused in a graphite crucible without a lining in order that the graphite might have a reducing effect upon the small quantity of oxide present, and the resulting fused copper be as free from it as was possible. The results of his experiments are given in Table I, and are represented graphically by the freezing-point curve in the diagram.

[1] *Mittheilungen aus den Königlichen Versuchsanstalten zu Berlin*, 1900, XVIII, p. 315. See also *The Metallographist*, 1903, VI, p. 49.

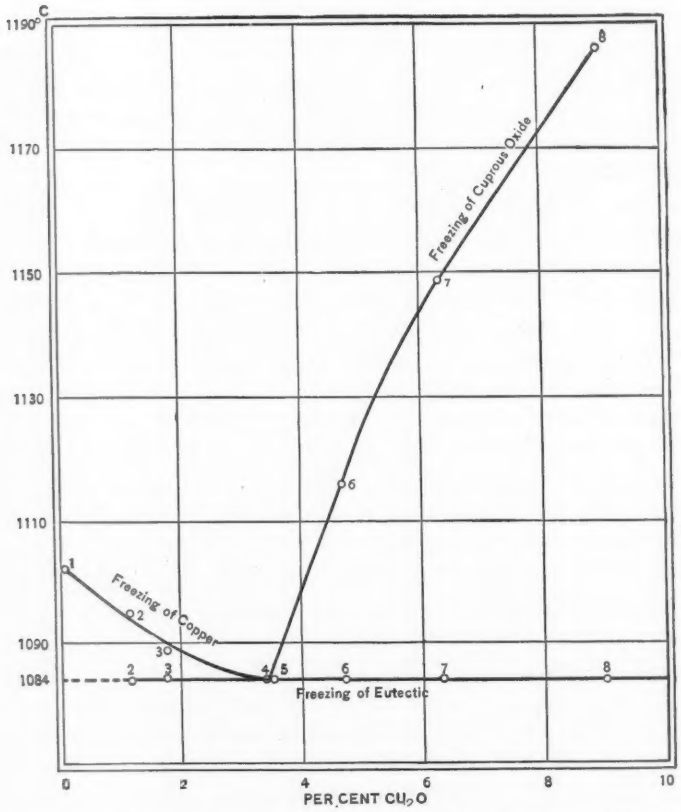

DIAGRAM.—FREEZING-POINT CURVE OF COPPER—CUPROUS OXIDE ALLOYS.

TABLE I.—RESULTS OF HEYN'S EXPERIMENTS.

Test number.	Charge.		Crucible lined or not lined.	Cu_2O calculated from O found by analysis.*	Temperature of Solidification.		Observations on the galvanometer.
	Cu Grams.	Cu_2O Grams.			Beginning.	Ending.	
				Per cent.	Degrees Centigrade.	Degrees Centigrade.	
1	450	None	Not lined	0.08	1,102	. .	Decided retardation at 1,102° C.
2	450	?	Lined	1.16	1,095	1,085	Long retardation at 1,095° C., slow fall to 1,083° C., quick rise to 1,085° C., long retardation, slow, followed by quick, fall.
3	450	9.0	Lined	1.75	1,089	1,084	Slow fall, beginning at 1,089° C., retardation at 1,086° C., slow fall to 1,083° C., sudden rise to 1,084° C., long retardation, slow, followed by quick, fall.
4	450	22.5	Lined	3.4	. .	1,084	Fall to 1,076° C. without any retardation, sudden rise to 1,084° C., long retardation, slow, followed by quick, fall.
5	450	18.0	Lined	3.5	. .	1,084	Fall to 1,082° C. without any retardation, sudden rise to 1,084° C., long retardation, slow, followed by quick, fall.
6	450	27.0	Lined	4.7	1,116	1,084	Slow fall beginning at 1,116° C., very slow fall to 1,076° C., sudden rise to 1,084° C., long retardation, slow, followed by quick, fall.
7	450	40.5	Lined	6.3	1,149	1,084	Slow fall beginning at 1,149° C., very slow fall to 1,077° C., sudden rise to 1,084° C., long retardation, slow, followed by quick, fall.
8	450	60.0	Lined	9.0	1,186	1,084	Slow fall beginning at 1,186° C., slow fall to 1,079° C., sudden rise to 1,084° C., long retardation, slow, followed by quick, fall.

* Reduction by means of hydrogen: "Hampe's Method," *Zeitschrift für Berg-, Hütten- und Salinen-Wesen in Preussen*, 1873, XXI, p. 231.

It will be seen from Table I that upon cooling only the tests Numbers 1, 4, and 5 show a single fall of temperature, which means that they do not pass through a pasty stage, but freeze suddenly. With the other tests there is a gradual freezing from the beginning to the end of the solidification. With all samples, excepting test Number 1, the cooling is accompanied by surfusion, the depressed temperature rising in every instance to the fixed point of 1,084° C. This temperature, corresponding to the freezing-points of tests Numbers 4 and 5 containing 3.4 and 3.5 per cent. Cu_2O respectively, which have only one distinct point of solidification, must be the temperature of the eutectic. The V-shaped freezing-point curve of the diagram, plotted

from the data in Table I, and the photo-micrographs, Figures 1 to 8 inclusive, bring this fact out clearly. Figures 4 and 5, the eutectic of copper and cuprous oxide with 3.4 and 3.5 per cent. Cu_2O respectively, show the characteristic structure, *i. e.*, a conglomerate of the two components arranged more or less in alternate plates which do not cross one another. With alloys of diminishing percentages of cuprous oxide, shown in Figures 3, 2, and 1, the micrographs give the dark network of eutectic and the light mesh-work of copper; with alloys having percentages of cuprous oxide greater than 3.4 or 3.5, the micrographs, Figures 6 and 7, show patches of cuprous oxide increasing in size imbedded in eutectic mixture.

The alloys of copper and cuprous oxide, when in the molten state, form homogeneous solutions similar to salt solutions. Upon the solidification of copper-alloys containing less than 3.45 per cent. Cu_2O, the cuprous oxide falls out completely and does not form a solid solution with copper. This is seen clearly in Figure 1, where the network of the eutectic is still visible, when the copper contains only 0.08 per cent. Cu_2O. Should any cuprous oxide form a solid solution, its quantity would have to be less than 0.08 per cent. Whether in an alloy with more than 3.45 per cent. Cu_2O the patches of cuprous oxide (Figures 6 and 7) are pure cuprous oxide is not settled, but in all probability this is the case.

Finally, Figure 8 represents the same sample as shown in Figure 2, viz., copper with 1.16 per cent. Cu_2O. In the first case the specimen has been heated to 1,100° C. and then quenched in water of 10° C.; in the second it has been allowed to cool slowly. The disconnected points in the micrograph of the quenched specimen show how the free development of the inner structure has been arrested; in contrast Figure 2 illustrates clearly how the eutectic, if given sufficient time, forms a connected network.

The leading statements of Heyn's paper, including eight of his nine micrographs, have been repeated here, for the reason that they have an important bearing upon the work to be described; in fact, the suggestion in his conclusions that observation of the microstructure of refined copper might be substituted for the lengthy determination of oxygen was the cause of undertaking the present investigation. This embodies the examination of fractures of samples taken in different stages of refining, the determination of the oxygen-content, the preparation of micrographs, and, lastly, the planimetric measurement of enlarged micrographs, with calculation of the percentage of oxygen.

Description of Samples.

Button-samples for this investigation were kindly furnished by Mr. W. T. Burns, of the Boston and Montana Consolidated Copper and Silver Mining Company, Great Falls, Montana; by Mr. M. B. Patch, of the Buffalo Smelting Works of the Calumet and Hecla Mining Company, Buffalo, New York; and by Mr. G. M. Luther, of the Nichols Chemical Company, Laurel Hill, New York.

Sample Number 1 of the Boston and Montana Company represents cathode copper after it has been melted down in the reverberatory furnace and skimmed, but not rabbled; Number 2 was taken after the rabbling had been completed and the stage of set-copper reached; Number 3 is the sample after the poling has been finished and the copper is ready to be ladled into wire-bars. The tests made at the works give: silver, 0.8 ounce per ton; arsenic and antimony, 0.0035 per cent.; conductivity, 97.5 per cent.; tensile strength, 64,200 pounds per square inch; elongation, 1 per cent.; torsion-twists in 6 inches, 89.

Sample Number 0 of the Buffalo Smelting Works represents set-copper; the remaining six of the set, Numbers 1, 2, 3, 4, 5, and 6, were taken at intervals of fifteen minutes during the poling-period: Number 1 was cast after the poles had been in the furnace for fifteen minutes; Number 6 is finished refined copper brought to a pitch at which ingots or cakes are cast. Samples Numbers A and B, from another charge, represent copper brought to ingot-pitch and wire-bar pitch respectively, special care having been taken to allow the samples to cool slowly.

The sample of the Nichols Chemical Company represents plate-pitch, *i.e.*, the pitch desired for casting thin electrodes.

Fractures of Samples.

The fractures reproduced in Figures 9 to 18 inclusive were prepared in the usual way. An incision about 0.125 inch in depth was made across the convex side of a button with a cold chisel, the button then clamped in a vise with the incision just protruding above the jaws, and given one or more shearing blows with a heavy short-handle hammer. With set-copper one blow was sufficient to break the specimen in two; the nearer the sample approached tough-pitch copper the larger was the number of blows required to obtain a fracture.

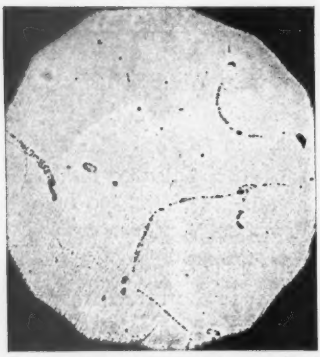

FIG. 1.—PHOTO-MICROGRAPH OF COPPER—CUPROUS OXIDE ALLOY.
0.08 per cent. Cu_2O. × 123. (Heyn.)

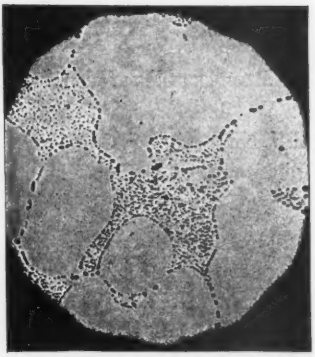

FIG. 2.—PHOTO-MICROGRAPH OF COPPER—CUPROUS OXIDE ALLOY.
1.16 per cent. Cu_2O. × 123. (Heyn.)

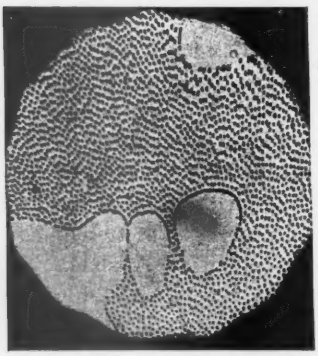

FIG. 3.—PHOTO-MICROGRAPH OF COPPER—CUPROUS OXIDE ALLOY.
1.75 per cent. Cu_2O. × 123. (Heyn.)

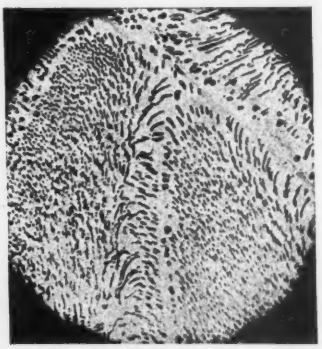

FIG. 4.—EUTECTIC OF COPPER AND CUPROUS OXIDE.
3.4 per cent. Cu_2O. × 123. (Heyn.)

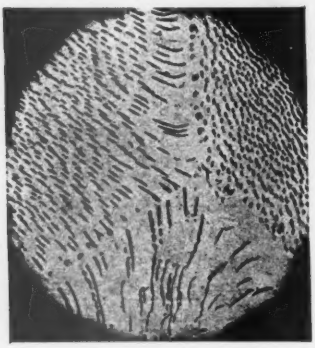

FIG. 5.—EUTECTIC OF COPPER AND CUPROUS OXIDE.
3.5 per cent. Cu_2O. × 123. (Heyn.)

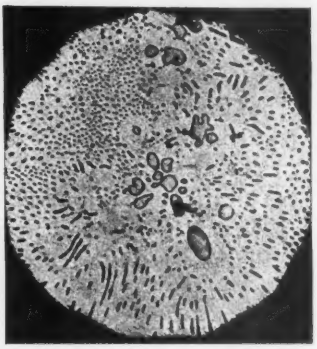

FIG. 6.—PHOTO-MICROGRAPH OF COPPER—CUPROUS OXIDE ALLOY.
4.7 per cent. Cu_2O. × 123. (Heyn.)

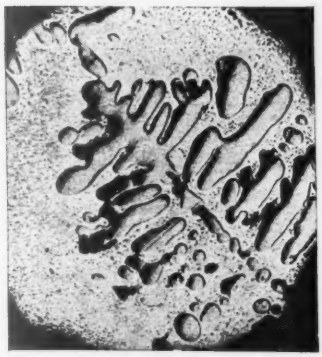

FIG. 7.—PHOTO-MICROGRAPH OF COPPER—CUPROUS OXIDE ALLOY.
6.3 per cent. Cu_2O. × 123. (Heyn.)

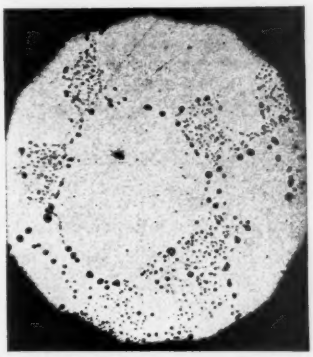

FIG. 8.—PHOTO-MICROGRAPH OF COPPER—CUPROUS OXIDE ALLOY.
1.16 per cent. Cu_2O. × 123. (Heyn.)

FRACTURES OF COPPER.

FIG. 9.—SAMPLE NO. 1, BOSTON AND MONTANA COPPER.
After melting, contains 3 per cent. Cu_2O (?). × 1.5.

FIG. 10.—SAMPLE NO. 2, BOSTON AND MONTANA COPPER.
Set copper, contains 6.16 per cent. Cu_2O. × 1.5.

FIG. 11.—SAMPLE NO. 3, BOSTON AND MONTANA COPPER.
Wire-bar, contains 0.51 per cent. Cu_2O. × 1.5.

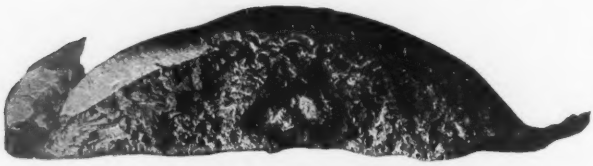

FIG. 12.—SAMPLE NO. 0, CALUMET AND HECLA COPPER.
Set copper, contains 5.76 per cent. Cu_2O. × 1.5.

FIG. 13.—SAMPLE NO. 1, CALUMET AND HECLA COPPER.
After poling 15 minutes, contains 5.67 per cent. Cu_2O. × 1.5.

FIG. 14.—SAMPLE NO. 2, CALUMET AND HECLA COPPER.
After poling 30 minutes, contains 3.36 per cent. Cu_2O. × 1.5.

FIG. 15.—SAMPLE NO. 3, CALUMET AND HECLA COPPER.
After poling 45 minutes, contains 1.86 per cent. Cu_2O. × 1.5.

FIG. 16.—SAMPLE NO. 4, CALUMET AND HECLA COPPER.
After poling 60 minutes, contains 1.98 per cent. Cu_2O. × 1.5.

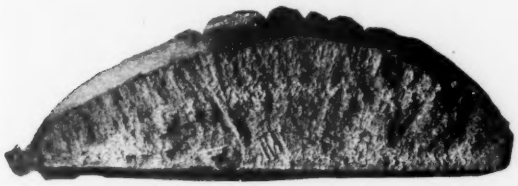

FIG. 17.—SAMPLE NO. 5, CALUMET AND HECLA COPPER.
After poling 75 minutes, contains 0.84 per cent. Cu_2O. × 1.5.

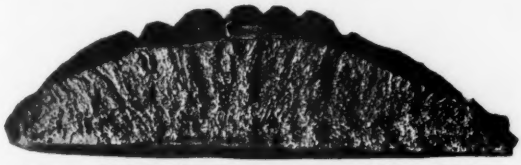

FIG. 18.—SAMPLE NO. 6, CALUMET AND HECLA COPPER.
After poling 90 minutes (ingot copper), contains 0.47 per cent. Cu_2O. × 1.5.

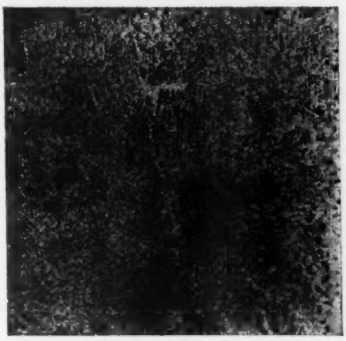

FIG. 19.—SAMPLE NO 1, BOSTON AND MONTANA COPPER.
Contains 3 per cent. Cu_2O (?). × 100.

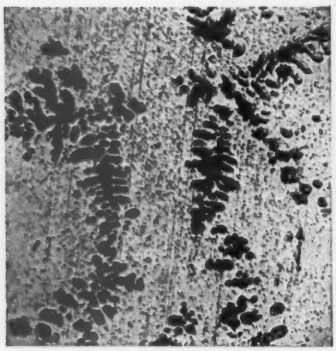

FIG 20.—SAMPLE NO. 2, BOSTON AND MONTANA COPPER.
Contains 6.16 per cent. Cu_2O. × 100.

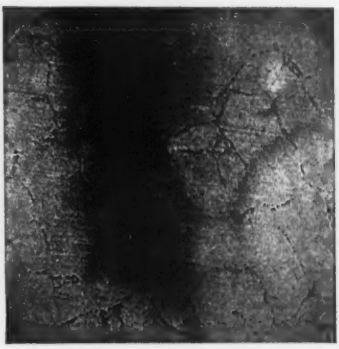

FIG. 21.—SAMPLE NO. 3, BOSTON AND MONTANA COPPER, WIRE-BAR.
Contains 0.51 per cent. Cu_2O. × 100.

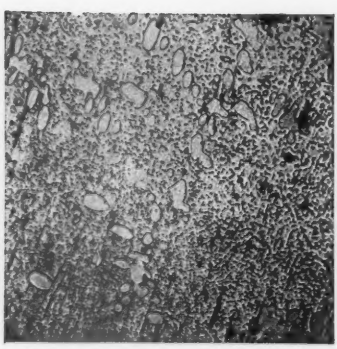

FIG. 22.—SAMPLE NO. 0, CALUMET AND HECLA SET COPPER.
Contains 5.76 per cent. Cu_2O. × 100.

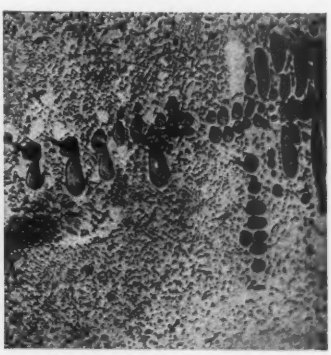

FIG. 23.—SAMPLE NO. 1, CALUMET AND HECLA COPPER.
After poling 15 minutes, contains 5.67 per cent. Cu_2O. × 100.

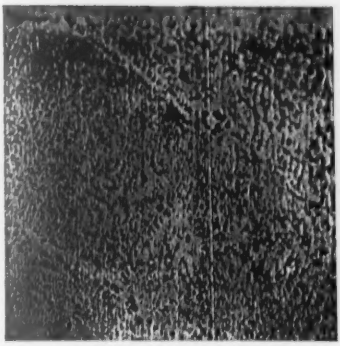

FIG. 24.—SAMPLE NO. 2, CALUMET AND HECLA COPPER.
After poling 30 minutes, contains 3.36 per cent. Cu_2O. × 100.

FIG 25.—SAMPLE NO. 3, CALUMET AND HECLA COPPER.
After poling 45 minutes, contains 1.86 per cent. Cu_2O. × 100.

FIG. 26.—SAMPLE NO. 4, CALUMET AND HECLA COPPER.
After poling 60 minutes, contains 1 98 per cent. Cu_2O. × 100.

FIG. 27.—SAMPLE NO. 5, CALUMET AND HECLA COPPER.
After poling 75 minutes, contains 0.84 per cent. Cu_2O. × 100.

FIG. 28.—SAMPLE NO. 6, CALUMET AND HECLA COPPER.
After poling 90 minutes, contains 0.47 per cent. Cu_2O. (Ingot copper cooled quickly.) × 100.

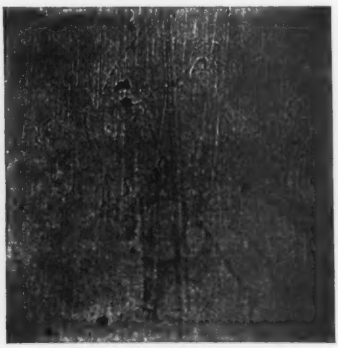

FIG. 29.—SAMPLE "A," CALUMET AND HECLA INGOT COPPER COOLED SLOWLY.
Contains 0.91 per cent. Cu_2O. × 100.

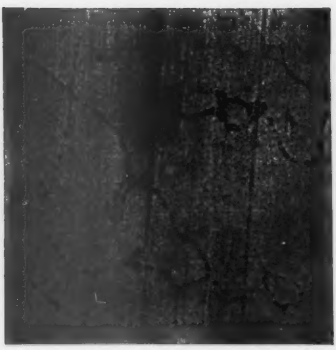

FIG. 30.—SAMPLE "B," CALUMET AND HECLA WIRE-BAR COPPER COOLED SLOWLY.
Contains 0.39 per cent. Cu_2O. × 100.

FIG. 31.—SAMPLE OF NICHOLS & CO.'S PLATE-COPPER.
Contains 0.28 per cent. Cu_2O. × 100.

Several experiments were made to find the best light and time of exposure necessary, the position of the specimen with regard to the light, and the proper magnification to bring out the details in a photograph. A reversible-back Premo camera, 4 by 5 inches, was used with sunlight, the specimen having been placed on a white background. Exposures of 40, 80, and 160 seconds were tried, using a Number 32 diaphragm. With negatives half the size, the same size, one and one-half times, and twice the size of the original, exposures of from 40 to 80 seconds gave good results. Trying back-light and side-light, it was found that the latter brought out the structure more satisfactorily than the former. A magnification of one and one-half was necessary to show clearly the details in the photograph.

As it is not easy to have constant conditions with sunlight, electric light from a 16-candle power incandescent lamp was substituted and an enlarging camera of E. and N. T. Anthony[1] used. With the light placed at about 5 inches from the specimen, so as to make an angle of 45° with the face, and using the middle diaphragm, an exposure of six minutes gave the best negative. With finely-granular fractures, filtering the light through ground glass was an improvement, but the time of exposure had to be prolonged to ten minutes; with the coarser structures better results were obtained without the ground glass.

Figures 9, 10, and 11 give the fractures of the Boston and Montana samples Numbers 1, 2, and 3 in one and one-half times their natural sizes. Figure 9, cathode copper after melting and skimming, but before rabbling, has a fracture radiated and columnar, luster is absent, the color a dark red. Figure 10 is set-copper, the fracture has lost its radial character and has become coarse-columnar to coarse-cubical; it remains dull, the color has changed to a brick-red; in the apex of the depressed surface there has appeared the characteristic single bubble. Finally, Figure 11 represents refined copper brought to wire-bar pitch; the fracture is finely-granular and fibrous, the luster is very silky, and the color roseate.

Samples Numbers 0 to 6 of the Calumet and Hecla Company, shown in Figures 12 to 18, begin with set-copper and end with ingot-copper. The fractures, starting from coarse-columnar and cubical (Figure 12), lose their columnar character, remaining coarse and cubical (Figure 13); they become coarsely radiated (Figure 14), then the radiation assumes finer forms and granulation puts in an appearance (Figure

[1] Address, Number 591 Broadway, New York City.

TABLE II. — Observations on Fractures of Sample-buttons.

Properties.	Boston and Montana.			Calumet and Hecla.						
	Samples			Samples						
	No. 1.	No. 2.	No. 3.	No. 0.	No. 1.	No. 2.	No. 3.	No. 4.	No. 5.	No. 6
Texture	Radiated, columnar	Columnar, cubical, coarse	Finely-granular, fibrous	Cubical, columnar, quite coarse	Cubical, coarse	Radiated, coarse	Finely-radiated, somewhat granular	Granular to finely-radiated	Finely-granular, with some fine radiation	Finely-granular
Luster	Dull	Dull	Very silky	Dull	Dull, with specks of silkiness	Dull, with increasing silkiness			Half dull, half silky	Nearly full silkiness
Color	Dark brick	Brick	Rose	Brick	Brick	Light brick	Light brick	Light brick to rose	Light brick to rose	Rose

15); granulation predominates over radiation (Figure 16), both become finer (Figure 17), until with Figure 18 radiation has been entirely replaced by granulation. In a similar manner the luster, from being absent with Figure 12, becomes at first slightly silky; then silkiness increases until full silkiness is reached with Figure 18. The dark brick-red color of Figure 12 becomes lighter (Figures 13, 14, and 15), rose-color begins to be seen (Figures 15 and 16), until full rose-color is reached with Figure 18.

The observations on the fractures are brought together in Table II.

Determination of Oxygen in Samples.

The oxygen of the different samples was determined by means of Hampe's method,[1] which consists in reducing the oxide of finely-divided copper (brought to a bright red heat) in a current of hydrogen, the loss in weight giving a measure for the oxygen-content. Hampe,[2] and later Heyn,[3] give evidence that the reduction is complete. The apparatus used and recommended by Hampe was somewhat modified, partly along the lines suggested by Archbutt,[4] and partly by changes which suggested themselves during the work. On account of the smallness of the samples, it was necessary to use less material for the analyses than did Hampe, viz., from 10 to 13 grams. The apparatus used consisted of a 16.5-inch Kipp gas generator (charged with hydrochloric acid and feather zinc), a gas-washing bottle filled two-thirds full with a saturated solution of caustic soda, a drying-tower with sticks of caustic soda, a U-tube filled with calcium chloride, a bulb-tube filled with copper borings, and a second U-tube filled with calcium chloride.

The bulb-tube, of Bohemian glass, $\frac{3}{16}$ inch thick, was 8 inches long and had a bulb 3 inches long and 1.25 inches in diameter. It was supported by a frame (5 inches long by 3 inches wide by 2.5 inches high) of "uralite" (an asbestos boarding) having slots 1.25 inches deep in the ends to receive the cylindrical ends of the bulb. The frame was

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[1] *Zeitschrift für Berg-, Hütten- und Salinen-Wesen in Preussen*, 1873, XXI, p. 231.

[2] *Op. cit.*, p. 234.

[3] *Zeitschrift des Vereins deutscher Ingenieure*, 1900, XLIV, p. 509; see also *Metallographist*, 1900, VI, p. 48.

[4] *Analyst*, 1900, XXV, p. 253.

placed on a thin sheet of asbestos paper[1] resting upon a ring-stand. Under this was placed a Tirrel burner with a flame spreader. The whole was enclosed by a frame of heavy asbestos matting (7 inches long by 6 inches wide by 13 inches high) with slots in the sides to receive the protruding cylindrical ends of the bulb.

The mode of procedure was as follows: from 20 to 25 grams of borings[2] were taken for a sample, small bits of iron were removed by a magnet, the borings were washed in a beaker four or five times with alcohol and dried to remove the last traces of alcohol, care being taken to avoid any oxidation of the copper. The borings were then divided into approximately equal parts, transferred to the weighed bulb-tubes, and weighed. A bulb was placed in the furnace, connected by rubber tubing with the train of hydrogen apparatus, hydrogen passed through for five minutes at the rate of six bubbles per second, the gas issuing from the second calcium-chloride tube ignited, and the bulb slowly brought to a bright-red heat. When water ceased to appear in the glass leading to the second calcium-chloride tube, the gas current was reduced so that only three bubbles passed the wash-bottle per second, and the bulb was kept at a bright-red heat for one and a half hours. At the end of this time the supply of gas was again increased to six bubbles per second, the lamp removed, and the copper allowed to cool. When cool the bulb was disconnected, air aspirated through it, and the bulb cleaned and weighed.

The results obtained are given in Table III.

It will be noticed that the average percentage of cuprous oxide of the Boston and Montana wire-bar copper is higher than that of the Calumet and Hecla cake-copper, although the former had been brought to a higher pitch and should, therefore, contain less oxygen. The discrepancy may be explained by the fact that the Boston and Montana copper contains more impurities than the Calumet and Hecla, and these impurities are present as oxides.

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[1] Asbestos was chosen after sheet-iron (used by Archbutt) had failed with the heating apparatus used, and copper had become oxidized and perforated too quickly.

[2] In boring the drill was run very slowly to prevent heating of the sample.

TABLE III. — DETERMINATIONS OF OXYGEN IN SAMPLES OF COPPER.

Sample.		Weight of copper used.	Weight of oxygen found.	Quantity of oxygen in copper.	Quantity of cuprous oxide in copper.
		Grams.	Grams.	Per cent.	Per cent.
Boston and Montana	No. 1	9.9251	0.0319	0.322*	2.88*
		10.2990	0.0347	0.337*	3.015*
	No. 2	10.1953	0.0702	0.688	6.159
		13.2269	0.0873	0.659	5.905
	No. 3	6.7495	0.0054	0.056	0.503
		6.7071	0.0048	0.058	0.523
Calumet and Hecla	No. 0	10.5543	0.0679	0.643	5.757
		11.5738	0.0744	0.643	5.755
	No. 1	12.6041	0.0791	0.628	5.618
		10.9386	0.0700	0.640	5.725
	No. 2	11.9961	0.0430	0.358	3.207
		12.1626	0.0456	0.375	3.360
	No. 3	11.8279	0.0242	0.205	1.830
		16.2051	0.3440	0.212	1.900
	No. 4	12.6454	0.2940	0.221	1.980
		13.8294	0.3080	0.223	1.990
	No. 5	13.3018	0.1250	0.094	0.841
		18.2256	0.1690	0.093	0.839
	No. 6	11.3544	0.0059	0.052	0.465
		12.2972	0.0072	0.058	0.524
		13.1625	0.0068	0.052	0.463

*These samples contained some sulphur, which was given off as hydrogen sulphide; the figures represent, therefore, oxygen plus sulphur, and not sulphur alone; and the figures in the last column ought to be too high, but, as seen by micrograph (Figure 19), they are very much too low.

MICROSCOPICAL EXAMINATION OF SAMPLES.

The pieces of copper used for making micro-sections were sawed out as nearly as possible from the centre of a fracture, as it was thought that some segregation might have taken place in the cooling. Later observations, however, showed that this precaution was unnecessary as long as the superficially oxidized surface was excluded. The samples were all finished with the polishing machine made by the Boston Testing Laboratories.[1] In using the machine for rough-polishing, the emery on the canvas-wheel pitted the surface to such an extent that it became necessary to file the specimen smooth before proceeding any further. In regular work, therefore, the sawed specimens were first treated with a rough, followed by a smooth, file, and then polished with rouge and water on a revolving wooden disk covered with broadcloth. In polishing, considerable difficulties were encountered at first, as the polished

[1] *Metallographist*, 1901, IV, p. 275.

surfaces, when examined under the microscope, showed disturbing scratches. Polishing by hand with rouge and water on a smooth board, covered first with sheet-rubber and then with chamois, gave a more lustrous surface than when the wheel was used, but at the same time it intensified the scratches. This pointed to the probable presence of coarse particles in the rouge. In order to remove them, about one volume of rouge was stirred up with two volumes of water in a beaker, allowed to settle for about thirty seconds, and the suspended matter applied with a brush to the broadcloth disk. The results were satisfactory, and all samples were treated in this manner. When polished, they were cleaned with alcohol and wiped dry with chamois. By thus applying the rouge, running of water on to the machine could be dispensed with, which made the whole operation cleaner. Experiments with the suspended rouge decanted from that which had settled, filtering, and then applying the filter-contents to the disk, did not work well.

In examining the polished sections with the microscope,[1] magnifications ranging from 30 to 750 diameters were tried. As a high magnification did not bring out the structure more clearly than did one of a smaller diameter, but only narrowed the field of observation, a comparatively low magnification of 100 diameters was chosen. This gave a magnification of about 230 diameters on the photographic plate. To the eye the contrast between the black[2] cuprous oxide in the eutectic (or the bluish-black excess-cuprous oxide in samples containing over 3.45 per cent. Cu_2O) with the red-colored copper was clearly visible, but the photographic plate failed to show it. In order to bring out the structure more clearly, various attempts were made to etch with nitric acid, sulphuric acid, silver nitrate, and with the electric current, but they did not improve matters. Heat-tinting did some good, but not enough. Yellow and orange-colored screens were then tried; of these the orange-colored glass proved to be the better, especially when a rapid isochromatic plate particularly sensitive to orange and yellow light was used for photographing. The orange light gave the copper a yellowish tint, but had little effect upon the cuprous oxide. The copper alone having an actinic effect upon the photographic plate, it appeared white in the positive, and the cuprous oxide black. The time of exposure giving the best results was found to be two and a half minutes.

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[1] Made by C. Reichert, Vienna (Bausch and Lomb Optical Company, Rochester, N. Y.).

[2] To Heyn, *op. cit.*, using chemically pure materials, it appeared bluish-black.

The Boston and Montana sample Number 1 (Figure 19), taken after melting and skimming the cathodes, is seen to contain a slight excess of cuprous oxide over the eutectic, although the analysis gives only 3 per cent. cuprous oxide. The black crystals are small, but easily distinguished from the cuprous oxide of the eutectic. Sample Number 2 (Figure 20), set-copper, contains a large excess of cuprous oxide over the eutectic; it shows fern-like forms which spring up in relief against the eutectic background. The fern-like forms are very unevenly distributed; the eutectic field in some places was free from them, in others it was entirely covered with them. Sample Number 3 (Figure 21), wire-bar copper, shows an evenly distributed fine network of eutectic enclosing large meshes of copper.

In the Calumet and Hecla series, sample Number 0 (Figure 22), set-copper, shows patches of excess-cuprous oxide in the eutectic. Sample Number 1 (Figure 23), taken fifteen minutes after poling had begun, does not differ much from sample Number 0, proving that the reduction had not proceeded very far. On the whole, both samples resemble very much the set-copper sample (Number 2) of the Boston and Montana, although they do not show the fern-like forms so clearly developed. The eutectic, in most cases, is slightly separated from the patches of excess-cuprous oxide crystals by a narrow band of copper, and the cuprous oxide in the eutectic seems to have separated somewhat from its copper, thus giving the field a spherulitic appearance.[1] In sample Number 2 (Figure 24), the third taken, reduction has progressed rapidly, but it still contains a slight excess of cuprous oxide over that of the eutectic mixture. It resembles sample Number 1 of the Boston and Montana series. In sample Number 3 (Figure 25) the eutectic has been passed, and the excess-copper becomes apparent. Sample Number 4 (Figure 26) shows that little progress was made in the reduction in the fifteen minutes that elapsed between the taking of samples Number 3 and Number 4. An explanation for this is that during this period, forty-five minutes after poling had begun, the poles were withdrawn and new ones put in their places. In sample Number 5 (Figure 27) the cuprous oxide is very much diminished, the eutectic forms a thin network enclosing copper in its meshes. Finally, sample Number 6 (Figure 28) represents refined copper brought to ingot-pitch. The network of the eutectic is imperfect and broken,

[1] See H. M. Howe, "Iron, Steel, and Other Alloys," Boston, 1903, p. 41.

and the dark parts of the eutectic are bunched together and larger than expected. The explanation of this peculiar structure may be found, when Figures 2 and 8 of Heyn's micrographs are compared, by the supposition that the sample was chilled when still above 1,084° C., the melting-point of the eutectic, which prevented the eutectic from separating out in the form of a continuous skeleton. In order to find out whether this idea was a correct one, a new sample (A), taken at the ingot-copper stage from another furnace-charge and cooled slowly, was obtained and examined. Figure 29 brings out clearly the difference between quick and slow cooling. Figure 30, sample (B), represents the same batch of copper when ready to be ladled into wire-bar, the sample having been also cooled slowly. The skeleton here also is seen to be continuous and not broken as in Figure 28.

Finally, micrograph Figure 31 represents a sample of copper from the Nichols Chemical Company which has been brought to plate-pitch, *i.e.*, the poling has been carried further than is the case with the highest degree of wire-bar pitch of the Calumet and Hecla Company.

Area Measurements.

Measurements of areas which gave Sauveur[1] such interesting facts seemed very promising when applied to samples of copper containing less cuprous oxide than the eutectic mixture. Measuring the copper-areas and deducting them from the total area would give the eutectic area, and from this the percentage of cuprous oxide could be readily calculated. It would be useless, if not impossible, to measure the areas of cuprous oxide in the eutectic; and on account of the unequal distribution of cuprous oxide in specimens with more cuprous oxide than the eutectic, the data would be misleading.

For the purpose of measurement, enlargements were made of sample Number 3 (wire-bar copper) from the Boston and Montana Company, of samples Numbers 3, 4, 5, and 6 (ingot-copper, chilled) from the Calumet and Hecla Company; also of sample A (ingot-copper, cooled slowly) and sample B (wire-bar copper, cooled slowly) from the Calumet and Hecla Company, and of the sample of plate-copper from the Nichols Chemical Company.

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[1] *Transactions*, XXVI, p. 878.

The enlargements measured 16 by 20 inches, giving five times the magnification of the micrographs, or about 1,150 diameters. A circle, 12 inches in diameter, was drawn on an enlargement, divided into four quadrants, and measurements made on each. The Amsler planimeter[1] was the instrument employed. It is commonly used for the measurement of indicator cards, and is accurate to 0.1 per cent. The copper areas on an enlarged micrograph were outlined with a pencil in order to facilitate measurement. All measurements were carried out in duplicate. It took from one and one-half to two hours to measure the copper-areas of a micrograph, the time varying with the clearness with which the edges of the eutectic were defined. Thus, samples Number 5 and especially Number 6 of the Calumet and Hecla series were very difficult to measure. In calculating the percentage of cuprous oxide in the eutectic, the figure 3.45 was chosen, being the average of Heyn's two determinations, 3.4 and 3.5.

The degree of accuracy of the measurements, carried out at least in duplicate, is shown by examples in Table IV, in which A–V represent the copper areas of one sample.

TABLE IV. — Planimeter Measurements of Copper Areas.

Copper area.	A.	B.	C.	D.	E.	F.	G.	H.
Square inches	2.35	1.04	1.61	2.24	0.27	10.17	2.56	8.26
	2.33	1.04	1.61	2.24	0.27	10.13	2.56	8.27
	2.35	. .	. .	. .	. .	10.14	. .	. .
Copper area.	I.	J.	K.	L.	M.	N.	O.	P.
Square inches	0.78	2.83	7.90	4.57	3.20	5.22	3.39	3.14
	0.78	2.83	7.87	4.57	3.20	5.20	3.42	3.12
	. .	. .	7.86	. .	. .	5.20	3.40	3.12
Copper area.	Q.	R.	S.	T.	U.	V.	. .	. .
Square inches	5.47	6.57	4.04	2.21	2.91	2.80	. .	. .
	5.45	6.53	4.01	2.21	2.87	2.80	. .	. .
	. .	6.57	4.00	. .	2.84	. .	. .	. .
	. .	. .	. .	. .	2.84	. .	. .	. .

[1] Made in Switzerland, and sold by the Crosby Steam Gauge and Valve Company, Boston, Mass.

The percentages of cuprous oxide resulting from the measurements in the several quadrants and the averages are given in Table V.

TABLE V. — PLANIMETER MEASUREMENTS OF QUADRANTS OF VARIOUS SAMPLES.

Sample.	First quadrant.	Second quadrant.	Third quadrant.	Fourth quadrant.	Average of quadrants.
No. 3 (Boston and Montana) . . .	0.58	0.52	0.36	0.48	0.49
No. 3 (Calumet and Hecla)	2.34	1.76	1.22	1.84	1.79
No. 4 (Calumet and Hecla)	2.00	1.37	1.95	2.06	1.85
No. 5 (Calumet and Hecla)	1.00	1.15	0.31	1.11	0.89
No. 6 (Calumet and Hecla)	0.39	0.93	0.61	0.30	0.56

It will be seen that the measurements of the quadrants of a sample show some discrepancies, as the copper islands are not uniformly distributed in the eutectic network. An excess of constituent in one quadrant is, however, balanced by a lack in another, giving on the whole a very satisfactory average.

The results obtained by fracturing and by chemical and microscopical analysis are brought together in Table VI.

The features relating to fractures have already been summarized. Comparing the cuprous-oxide content obtained by chemical analysis and by planimetric measurement, it will be seen that the percentage of cuprous oxide found by analysis in the Boston and Montana sample Number 3, and in the Calumet and Hecla samples Numbers 3 and 4, is somewhat higher than that by measurement. This may be due to the fact that the chemical analysis gives the total oxygen — that of the copper as well as that of the impurities — while measurement gives only the oxygen of the copper. That the oxygen found by analysis in the Calumet and Hecla samples Numbers 5 and 6 is lower than that obtained by measurement is probably due to the segregation of the cuprous oxide in the eutectic, causing the latter to spread somewhat. Taking the results as a whole, they show that area measurements of enlarged micrographs of pure coppers containing less oxygen than the eutectic give good valuations of the oxygen-content. Further, it seems entirely feasible to make quickly a close estimation of the percentage of cuprous oxide contained in a sample of copper by simply examining a polished surface with the microscope, when once some experience has been gained. The mode of operating might be as fol-

TABLE VI. — Physical Characteristics and Corresponding Content of Cuprous Oxide and Oxygen in Various Samples.

Mark of sample.		Boston and Montana.			Calumet and Hecla.									Nichols Chemical Company.
		No. 1.	No. 2.	No. 3.	No. 0.	No. 1.	No. 2.	No. 3.	No. 4.	No. 5.	No. 6.	A.	B.	
Fracture		Radiated, columnar	Columnar, cubical, coarse	Finely-granular, fibrous	Columnar, cubical, coarse	Cubical, coarse	Radiated, coarse	Finely-radiated, somewhat granular	Granulated to finely-radiated	Finely-granular, finely-radiated	Finely-granular, finely-radiated	Finely-granular, finely-radiated	Finely-granular, fibrous	Finely-granular
Luster		Dull	Dull	Very silky	Dull	Dull, specks of silkiness	Dull, more silkiness	Dull, more silkiness	Less dull, more silkiness	Half dull, half silky	Nearly full silkiness	Nearly full silkiness	Full silkiness	Less silky than A
Color		Dark brick	Brick	Rose	Brick	Brick	Light brick	Light brick	Light brick to rose	Light brick to rose	Rose	Rose	Rose	Rose
Per cent. of cuprous oxide	by analysis	3.00	6.16	0.51	5.76	5.67	3.36	1.86	1.98	0.84	0.47	. .	. .	. .
	by measurement	. .	. .	0.49	. .	. .	. .	1.79	1.85	0.89	0.56	0.91	0.39	0.28
Per cent. of oxygen	by analysis	0.33	0.69	0.057	0.64	0.63	0.38	0.21	0.22	0.094	0.053	. .	. .	. .
	by measurement	. .	. .	0.055	. .	. .	. .	0.20	0.21	0.099	0.063	0.102	0.043	0.031

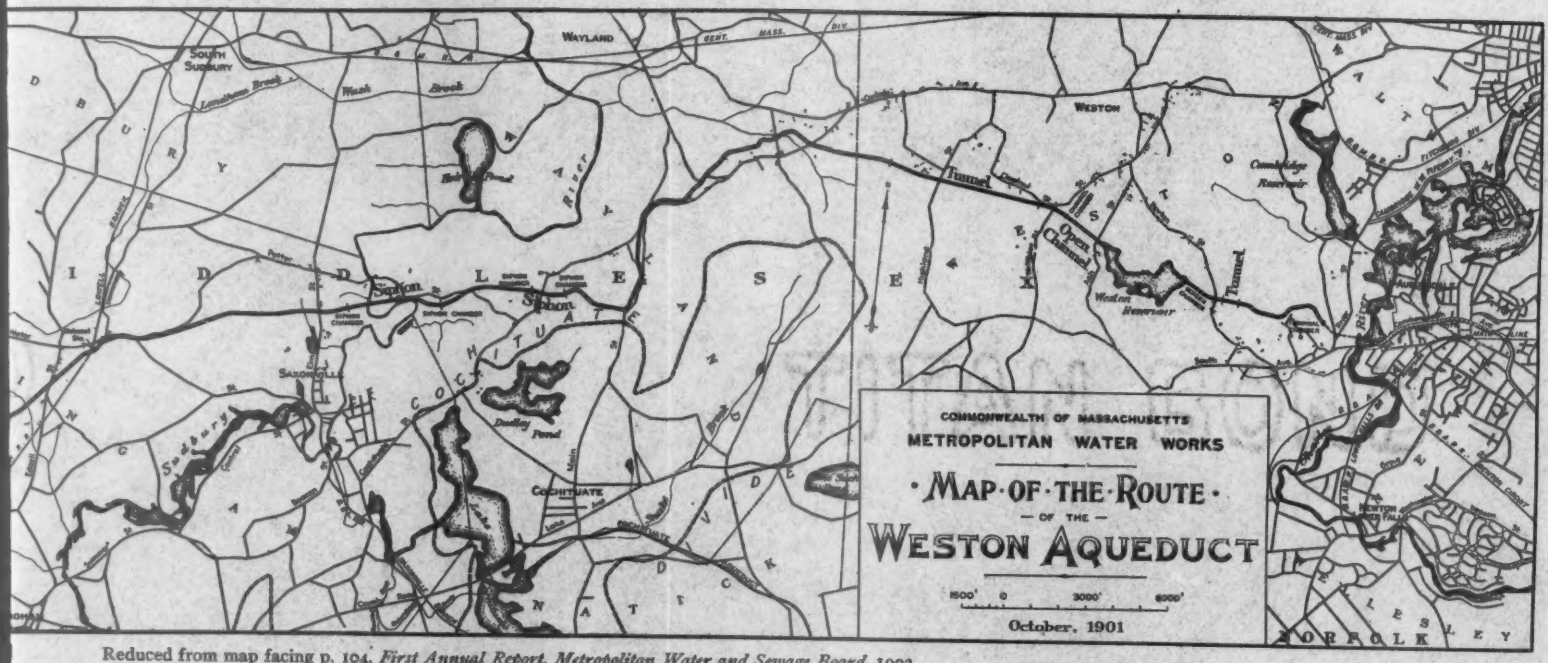
lows: to take a button-sample, cool it slowly, and quench it when it had solidified, cut out a piece with a circular saw, grind it smooth on a number of revolving wooden disks covered with emery-cloth or on revolving files, polish with rouge and water on a revolving disk covered with broadcloth (a mirror-like surface would not be necessary), and estimate with the microscope the percentage of cuprous oxide present. The whole operation could be done in from six to eight minutes. The poling could then be controlled by the microscope, and the degree of pitch desired for ingot-, large or small cake-, wire-bar-, or electrode-copper defined by a readily ascertainable amount of cuprous oxide that should be present.

In conclusion, we wish to thank Professors Richards and Fay for many valuable suggestions made during the course of the investigation.

METROPOLITAN WATER WORKS
MAP OF THE ROUTE
WESTON AQUEDUCT

Reduced from map facing p. 104, *First Annual Report, Metropolitan Water and Sewage*

and Sewage Board, 1902.



Reduced from map facing p. 104, *First Annual Report, Metropolitan Water and Sewage Board*, 1902.

GEOLOGY OF THE WESTON AQUEDUCT OF THE METROPOLITAN WATER WORKS IN SOUTHBORO, FRAMINGHAM, WAYLAND, AND WESTON, MASSACHUSETTS.

By W. O. CROSBY.

Introduction.

This new aqueduct of the Metropolitan Water Works, nearly fourteen miles in length, and now recently completed, traverses in a general east-west direction the region of crystalline rocks lying immediately to the west of the Boston Basin. In fact, the aqueduct may be regarded as affording an east-west section of the western rim of the Boston Basin. This is an area of almost unbroken drift deposits, and the widely scattered and often obscure or uncertain outcrops are quite insufficient to give a clear idea of the geological structure. The drift itself is chiefly modified, and hence of little value as a clue to the immediately underlying bed rock. Across the broad plains of stratified sand and gravel, which rise but little above the 200-foot contour, the aqueduct rarely encounters the bed rock; but where it pierces the till-clad hills it is almost constantly in solid rock, showing that these elevations, although typically drumloid in form, are really prominent rock protuberances more or less thickly veneered with till, or ground moraine. This study was restricted to the hard rocks almost exclusively, and it is proposed to notice the drift only incidentally where it presents features of special interest that might otherwise escape observation and record. In fact, the special purpose of this paper is to place on record the principal facts in regard to the character and structure of the hard rocks which were exposed to observation only temporarily during the construction of the aqueduct, and since the rocks were rarely encountered except in the tunnels, it is to the geology of the tunnels especially that the paper relates.

The aqueduct, the general course of which is shown on the accompanying map, embraces five tunnels, ranging from 600 to 5,686 feet, and aggregating 12,165 feet, in length. These may conveniently be

designated by number, beginning with the most westerly; and distances on the line of the aqueduct find convenient expression in the engineers' station numbers.

Tunnels 1, 2, and 3, it will be observed, are near the western end of the aqueduct, and tunnels 4 and 5 near the eastern end, while midway between these two groups of tunnels we have the broad valley of the Sudbury River and an unbroken expanse of modified drift. The distance, following the line of the aqueduct, between tunnel Number 3 and tunnel Number 4 is 39,651 feet; but tunnel Number 4, the longest of the series, would be far longer but for the fact that the aqueduct makes the great bend to the north in Wayland to pass around Reeves Hill. The elevation of the floor of the aqueduct ranges from about 215 feet at the western end near the Sudbury Dam to 200 feet at the eastern end south of Doublet Hill in Weston.

A systematic presentation of the facts temporarily brought to light during the construction of the aqueduct will be followed by such generalizations as they seem to warrant.

The Sudbury Dam.

The central part or spillway of this dam, the construction of which brought into existence the great reservoir known as Basin Number 5, rests upon ledges of granite and metamorphic sediments which are clearly older than the granite. The sediments consist chiefly of quartzite, mostly of a compact and slaty character and shading into well-defined and distinctly fissile mica schist. As now exposed at the foot of the dam, about 75 feet in breadth of these strata, striking approximately east-west and dipping north about 45 degrees, is bordered in that direction, or northward, by a similar breadth of granite, through the middle of which runs a layer, 2 to 3 feet in breadth, of a very soft and highly fissile mica schist, showing the same dip and strike as the main body of schist and quartzite. The granite contacts are thus seen to be structurally conformable, but that they are entirely igneous there seems no reason to doubt. The granite is the rather coarsely crystalline, pinkish, biotite granite characteristic of the region and related in character to the granite quarried in Milford. The structure of the granite is massive in the main, but near the contact with the sedimentary rocks it becomes much finer in grain and distinctly gneissoid, this lamination being, apparently, best interpreted as an original flow

structure. It is on the fluidal structure of the granite that we must depend chiefly for proof of its igneous relation to the sediments, the metamorphism of which, it may be assumed, dates, chiefly at least, from the intrusion of the granite. It may be noted, however, that several obscure apophyses of the granite penetrate the metamorphic rocks.

The borings and excavations made in connection with the construction of the Sudbury Dam show that the surface of the bed rock, while somewhat uneven or ridgy, lies mainly, as in the natural outcrops, between elevations 195 and 220; but a boring 400 feet northwest from the gatehouse gives the elevation of the ledge as about 171 feet. This boring indicates a quite deep bed-rock valley, the course of which must, apparently, lie across the southwest end of the dam where a deep excavation for the foundation of the dam failed to expose the bed rock. This supposition appears to be necessary because the indications are very plain that toward the northeast end of the dam the undulating bed-rock surface continues to rise, although it is covered here by from 20 to 30 feet of drift. The large mass of rock directly above the northeast end of the dam is quite possibly a bowlder, but, if so, it is probably resting on or near the surface of the ledge. Between 500 and 600 feet northwest of this point on the shore of the reservoir, at elevation 260, are ledges of quartzite, and on the summit and eastern slope of this ridge, bounding the reservoir on the northeast and almost directly opposite the end of the dam, are prominent ledges of granite. There seems to be no reason to doubt, therefore, that this is mainly a rock ridge thinly covered with drift and forming here the northeast slope of a valley, the rock bottom of which lies, as stated, mainly between elevations 220 and 195; but through this valley there probably runs a narrow, inner valley or gorge, the rock bottom of which must be at least as low as 170. In other words, the bed rock exposed or proved under the middle and northeasterly portions of the dam may be regarded as a sort of uneven terrace between the hypothetical gorge toward the southwest and the rocky ridge toward the northeast.

Tunnel Number 1.

This tunnel, 704 feet in length, pierces the narrow and steep-sided southeastern extension of the ridge which bounds the reservoir on the northeast. The contours of the ridge are here distinctly drumloid, and the tunnel has confirmed the indication of the preliminary borings

that this part of the ridge consists wholly of drift, showing that between the northeast end of the dam and the tunnel the bed rock falls off rather abruptly. The western end of the tunnel cuts through the bottom of a large and deep borrow pit in typical till, and all the surface indications are favorable to the view that the ridge consists throughout of till, or ground moraine. This is proved to be the case, however, only toward the northeast side of the ridge. For more than half its length from the western end the tunnel is wholly in stratified clay in which stones are sprinkled more or less freely, the stones varying in size from minute fragments up to masses a foot or more in diameter. At some points the stones are bunched so as to give the appearance of a true bowlder clay; but there are numerous streaks and patches of fine sand and quartz flour in the clay, and the stratification of the clay is fairly distinct at most points, although everywhere much disturbed and even contorted, being rarely horizontal and sometimes nearly vertical. Upward the stratified clay seems to be somewhat intermingled or mixed with the till, and the junction, if not lacking in distinctness, is at least very irregular. The stratified clay clearly indicates a temporary recession of the ice sheet and a body of standing water, with floating ice as an explanation of the erratics in the clay. In the subsequent readvance of the ice we have a natural explanation of the thrust which has disturbed and contorted the clay.

That the stratified clay is local and confined to comparatively low levels is indicated by the fact that it was not found in the northeastern end of the tunnel, nor in the borrow pit on the southwest side of the reservoir, nor in the old brickyard near the railroad.

From the eastern end of tunnel Number 1 the aqueduct crosses half a mile of approximately level modified drift to the western end of tunnel Number 2.

Tunnel Number 2.

This tunnel, with its western portal at Station 42 + 20, has a length of 3,015 feet, all the way in rock; and the approaches to the tunnel increase the continuous rock section to 3,200 feet or approximately from Station 42 + 00 to 74 + 00.

Granitic Rocks.—The rock is chiefly a coarse-grained biotite granite, varying from gray to pinkish in color. The biotite is in general, however, very much affected by hydration and chloritization; and ill-defined

greenish stains of both epidote and chlorite are common features of the granite, the epidote apparently derived from the feldspar and the chlorite from the biotite. The quartz is, in the main, finely granulated. There is much evidence of shearing and crushing, well-defined shear zones are of frequent occurrence, and a large part of the granite is in a semi-crushed condition with the incipient fragments enveloped by films of secondary sericite.

Toward the eastern end of the tunnel the granite is, aside from the shear zones, more commonly of a gneissoid character, and in some parts, especially east of Station 68 + 00, the lamination is very strongly marked. Where most typically developed, the quartz and feldspar individuals are drawn out into thin, unbroken lenses. The strike of the lamination or gneissic structure is usually about east-west or east-northeast, approximately parallel with the tunnel, and it dips to the north at high angles. Both the normal and gneissoid granites are cut by occasional irregular dikes and masses of a fine-grained, pinkish granite. This fine granite is poor in mica and of a distinctly aplitic character. The granite is throughout much jointed, and especially noticeable is a series of master joints, trending in a general east-west direction with northerly hade and often accompanied by shear zones and slickensides.

Basic Dikes. — The granitic rocks are intersected by two series of basic dikes, one series trending in a general east-west direction with northerly dip, parallel with the master joints just referred to and the gneissic structure of the granite, while the other has a nearly due north-south trend and is approximately vertical, the prevalent hade being at a low angle to the east. The two series of dikes are strongly contrasted in character as well as in trend and hade, and the east-west series is clearly the older, appearing to antedate, in part at least, the movement and general deformation of the granite. The dike rock is dark gray to black in color, evidently of a highly basic character. The microscopic examination of thin sections shows that the north-south dikes consist of normal diabase with numerous beautifully fresh and very slender phenocrysts of plagioclase in a finely crystalline or compact ground mass; and there seems to be no doubt that the east-west dikes were originally of similar character; but, having shared in the deformation of the granite, they are themselves highly metamorphic, being in general decidedly micaceous (biotitic) and chloritic and often exhibiting a marked foliated structure. In fact, the east-west

dikes are so far altered that without clearly exposed contacts they might not always be readily identified as of igneous origin.

The east-west dikes, hading north, comformably with the master joints, 20 to 60 degrees, begin at the western portal, where a dike at least 15 or 20 feet wide, with a strong hade to the north, fills the tunnel, and bearing to the south finally passes out of the tunnel at Station 43 + 50. A second dike 6 to 8 feet wide, with similar hade, first appears on the north side of the tunnel at Station 47 + 00 and goes out on the south side at Station 47 + 50. These two dikes are of fairly massive character or only moderately schistose, but toward the eastern end of the tunnel, where the gneissic structure is most marked in the granite, the dikes of this series are also most highly foliated, so that the rock would often pass for micaceous (biotitic) or chloritic schist. They have evidently suffered great compression and dynamic metamorphism, and are much split up by lenses of granite, the trap appearing in many cases to have been forced by the mechanical pressure into the joints or seams of the granite. They were specially noted east of Station 68 + 00, where the east-west joints of the granite are marked by several very distinct zones of black schist, lying at all angles and varying in width up to 5 feet or more. A specially interesting dike of this series, about 12 feet in width, follows the south side of the tunnel from about Station 70 + 00 to the eastern portal at Station 72 + 60, and indefinitely farther along the open cut, its trend being almost exactly parallel with the tunnel.

The north-south dikes were observed chiefly in the eastern half of the tunnel. These dikes are relatively narrow, varying from less than 1 foot to about 4 feet in width, and, as previously noted, are approximately vertical, with a prevalent easterly hade. At Station 66 + 60 a 3-foot vertical dike of this series is very extensively decomposed, being, in part, completely kaolinized. It is cut obliquely by a vertical fissure vein containing quartz, calcite, and pyrite, varying in width from 3 to 12 inches, and enclosing many angular fragments of the trap. A 4-foot vertical dike of this series showing relatively little kaolinization crosses the tunnel at Station 68 + 60. A transverse columnar structure is well developed, as in most of the dikes of this series where it has not been obliterated by kaolinization. At the eastern portal, Station 72 + 60, a very fresh dike of this series, 3.5 to 4 feet wide and hading east 25 degrees, cuts the large east-west dike previously described, and sends a 30-inch branch longitudinally westward into the large dike. Columnar jointing is well developed in both the main dike and the branch.

Additional features of interest in the geology of this tunnel are the development of more or less epidote, sometimes in the granite but usually in the longitudinal or east-west dikes, and the occurrence of well-marked slickensides of hematite in some of the joint cracks of the granite.

Tunnel No. 3.

This tunnel extends from Station 113 + 10 to 134 + 70, all the way in rock, and the open cut beyond the eastern portal makes the continuous rock section approximately 2,400 feet. It pierces a broad and somewhat composite drumloid with a high rock foundation and closely bordered on the west by a relatively low drumloid of the same type. Beneath the slightly marked depression separating the two drumloids, between Stations 121 + 50 and 122 + 00, the roof of the tunnel is in bowlder clay, while the rock section remains unbroken in the floor of the tunnel.

Granitic Rocks. — The western portal is in the fine, pinkish, aplitic granite, which extends nearly to Station 114 + 00. Beyond this the normal granite prevails, but there is more or less of the fine granite alternating with it. The normal granite is, in part, less coarse than in tunnel Number 2 and rather more inclined to a porphyritic habit. It is rarely distinctly gneissoid, but shear planes and sericitic films characterize nearly all parts of it, so that it is, on the whole, distinctly less sound and stable than the normal granite in tunnel Number 2.

Basic Dikes. — The dike phenomena of tunnel Number 2 are repeated in this tunnel, and both series are well developed.

The east-west dikes first appear at the western portal, which, as noted, is in fine granite, but with one of these highly altered and foliated dikes exposed at the bottom on the south side and hading north as usual. Continuing eastward, the dike rises nearly to the roof and then rapidly subsides and leaves the tunnel about 40 feet from the portal, its full width being nowhere exposed. Between Stations 114 + 05 and 114 + 35 a foliated, black dike, only 1 to 2 feet wide, crosses the tunnel obliquely, coming in on the south side and going out on the north side, and hading southeast 40 degrees. This phenomenon is repeated between Stations 115 + 45 and 115 + 65, a dike 5.5 feet wide coming in on the south and going out on the north as before and hading southeast 20 to 30 degrees; and again between Stations 116 + 35 and 116 + 70 and Stations 117 + 70 and

117 + 90, the dikes, which in these cases are from 6 inches to 2 feet wide and nearly vertical, crossing the tunnel obliquely from south to north as before. The observations were not continued through the middle of the tunnel; but toward the eastern portal another well-characterized dike of this series was noted between Stations 130 + 50 and 130 + 90, with the same trend and hade as before. The relations of these dikes to the tunnel show their true course to be more nearly northeast-southwest than east-west; and it is interesting to observe that they are throughout parallel with the principal shear zones of the granite.

The north-south dikes include the following, and probably others in the middle section of the tunnel which have escaped observation. At Station 119 + 75 a 3-foot dike hades east 10 degrees. It is cross jointed and divided on the south side of the tunnel by a slab of granite from 4 to 6 inches in thickness. A similar dike, but without the inclusion of granite, crosses near Station 122 + 00. Farther east the following group of dikes occurs:

Station 129 + 10, width 3 feet, hade east 10 degrees.
Station 129 + 20, width 4 feet, hade east 10 degrees.
Station 129 + 90, width 3.6 feet, hade east 10 degrees.
Station 130 + 15, width 2.3 feet, hade east 20 degrees.
Station 130 + 25, width 1 foot, hade west 10 degrees.
Station 131 + 80, width 2.5 feet, hade east 15 degrees.
Station 131 + 90, width 2.5 feet, hade east 15 degrees.
Station 131 + 95, width 3.5 feet, hade east 15 degrees.

The north-south dikes of this tunnel, like those of tunnel Number 2, are usually distinctly cross jointed or columnar in structure, but they are distinguished by being finer grained, and the lath-shaped phenocrysts are either wanting or relatively inconspicuous. They show throughout a marked tendency to decompose, or weather, into a rusty brown earth, and the samples illustrate every stage of the process.

Tunnel Number 4.

This tunnel is 5,686 feet long, extending from Station 529 + 93 to 586 + 79. Like tunnel Number 3, it pierces two drumloids of very unequal size, the eastern drumloid being a large and composite hill on the lee slope of which the outcrops rise almost to the summit, while the western drumloid as before is relatively low and flat and shows no outcrops, so that it might fairly be called a drumlin. The floor of the

tunnel is in rock for its entire length, but through the western hill the roof is in till from the portal to Station 538 + 85, or nearly 900 feet. This tunnel is not only longer, but it is geologically much more varied than any of the others, since to the granitic rocks and the basic dikes we have added important developments of metamorphic sedimentaries and of diorite. We may conveniently describe the formations in the order of age, and then trace their distribution and structural relations from west to east.

Sedimentary Rocks. — The predominant type of sedimentary rock is a massive, vitreous quartzite, varying in color from light to very dark gray. It is in part highly crystalline and not easily distinguished from ordinary vein quartz, but of its sedimentary origin there can be no doubt, and in large part it is a very normal quartzite, sometimes very distinctly stratified and grading through more compact varieties into a more or less siliceous argillite or hornstone. These rocks in all their various phases are abundantly displayed in the stone walls of Weston, but are rather rarely clearly exposed in the natural ledges; and the tunnel afforded a very exceptional opportunity to determine their structural relations.

Diorite. — The diorite appears to be the normal type so abundantly and widely associated with the granitic rocks of eastern Massachusetts, varied in texture from rather coarsely to very finely crystalline, and rather seldom porphyritic. The more compact varieties are dark gray to black in color, and the ferro-magnesian constituents appear to include both hornblende and biotite. Secondary epidote and chlorite are often abundant, as are also calcite and quartz, the latter especially occurring in more or less definite veinlets ramifying through the diorite. Not infrequently also the diorite is distinctly pyritiferous, and perhaps this, too, may best be regarded as a secondary feature of the composition, as is suggested by the occurrence of pyrite in the veinlets of quartz and calcite. These veinlets, with their massive structure and enclosed fragments and sheets of the diorite and beautifully slickensided walls, are clearly of exogenous origin. The association of the diorite with the metamorphic sedimentaries is such as to suggest that its normal position in the batholite is peripheral.

Granitic Rocks. — The normal and fine granites do not differ essentially from the corresponding types in the western tunnels. Much of the normal granite is rather exceptionally coarse; it is in part distinctly porphyritic, the phenocrysts of bright red feldspar being sometimes half

an inch to an inch in length; and in part also it exhibits a very perfect gneissic structure, identical in character with that described in the granite of the western tunnels. Aside from the gneissic structure, the normal granite is, however, rather more massive, showing less shearing and crushing with the accompanying sericitic developments. It is, however, very generally clouded and veined with epidote. As variations from the normal granite we have veinlets of pegmatite at one extreme, and at the other veinlets and larger masses of fine granite. Every phase of the granite may cut and enclose both the diorite and the sedimentary rocks, although the fine granite occurs most characteristically in this relation. In the deeper parts of the tunnel the normal granite and also the fine granite are prevailingly gray rather than reddish in color, leaving no room to doubt that the red and pink tints are the result of superficial oxidation.

Basic Dikes. — Trap dikes are relatively unimportant throughout this tunnel, and present no features tending to differentiate them from the dikes in tunnels 2 and 3.

Distribution and Relations of the Rocks. — Beginning at the western portal, the formation is essentially all diorite, relieved only by occasional dikelets of the granitic rocks, for approximately 2,000 feet; quartzite then begins to appear, and east of Station 550 + 00 is the prevailing rock for several hundred feet. Between Stations 553 + 00 and 553 + 20 an irregular mass of diorite breaks through the quartzite on the north side of the tunnel, and between this and Station 554 + 00 it is practically all quartzite on the north side of the tunnel and diorite on the south side. Beyond this the quartzite begins to assume at intervals a slaty character, and alternates frequently with the diorite, the contacts being always sharp, highly irregular, and clearly igneous. It is very evident that we have in this section of the tunnel a perfect complex of the quartzite and diorite, the relations being such, however, as to leave no doubt that the diorite is the younger and intrusive rock. Notwithstanding its irregular relations to the quartzite, the diorite is throughout of a quite remarkably uniform character, varying from finely crystalline to quite compact in texture, and often characterized by veinlets of secondary epidote and calcite, the calcite veinlets especially being at times a quite striking feature of the formation. These conditions continue practically unchanged to about Station 569 + 00, the quartzite becoming in this direction, in large part, of a slaty character, and being relieved toward the end by irregular and dike-like intrusions of fine granite.

Beyond this the normal granite begins. It is at first of a somewhat gneissic character, but becomes more massive eastward or away from the sedimentary rocks, although for a considerable distance it is interrupted at intervals by irregular bodies of diorite and some slate and quartzite. With these exceptions the normal granite is practically unbroken to the eastern portal, save for occasional irregular masses of fine granite, the smaller and more dike-like of which may be microcrystalline or even felsitic.

Although the basic dikes are few in this tunnel, both series are represented. In the general absence of shearing and crushing in the granite and diorite, the dikes of the east-west series are naturally less schistose in structure and more normal in composition, while the north-south dikes show no essential change from those of the western tunnels. Among the north-south dikes we have larger examples than have been noted before: thus between Stations 538 + 60 and 538 + 95 the tunnel is crossed by a rusty or highly oxidized dike about 25 feet wide; another, less altered and about 20 feet wide, was observed near Station 552 + 50. Other examples of this series were noted at Stations 572 + 45 (3 feet wide), 574 + 40 (14 feet wide), 578 + 95 (3 feet wide), and 585 + 35 (2 feet wide). The hade of the north-south dikes is sometimes east and sometimes west, but usually small, although one example, only 6 to 10 inches wide, in the vicinity of Station 583 + 00, is nearly horizontal. Possibly, however, this is a branch of some dike of more normal attitude — and in this connection it may be noted that, in the diorite especially, and with the feeble illumination of the tunnel, dikes are easily overlooked.

To summarize the geology of tunnel Number 4: we have, beginning at the west end, first, approximately 2,000 feet of diorite varied only by occasional small dikes of fine granite and one or two dikes of trap; second, nearly 2,000 feet of alternating diorite and metamorphic sedimentary rocks (quartzite and flinty slate or hornstone); third, nearly 2,000 feet of normal granite with a few included masses of diorite and of quartzite or slate. Basic dikes are few, and, although both series are represented, present no novel features, save that the longitudinal dikes show less dynamic metamorphism than in the western tunnels.

Near the eastern end of the tunnel, or east of Station 580 + 00, the normal granite is overlain by a quite remarkable assemblage of large granite bowlders, many of them 10 to 20 feet in diameter. We have here virtually a glacial moraine extending in a general northwest

and southeast direction along the base of the main hill. Excavations show that the bowlders are, in part, closely packed, resting directly one on another with only enough finer material to fill or partially fill the interstices.

Weston Reservoir.

The construction of the Weston Reservoir between tunnels 4 and 5 has involved a large amount of stripping and excavation and the exposure of the bed rock over considerable areas, especially in the lower, eastern part of the basin and on and near the line of the dam. The formation here is seen to be chiefly normal granite enclosing a small amount of diorite and alternating with some large as well as small bodies of fine granite. In some cases the contacts are indistinct or blending, the normal granite shading into the fine granite; and it is obvious that in this region, as elsewhere in the Boston Basin, the fine granite is in part contemporaneous with or older than the normal granite, and in part a later intrusion.

This complex of granitic rocks is cut at frequent intervals by dikes of greenstone diabase varying in width up to 15 feet or more. The prevailing trend is east-southeast, but they are very irregular and much split up by the granite, of which they enclose fragments and slabs. Nearly all are highly chloritized, typical greenstone, but a few are hard, dark gray, and finely porphyritic. They correspond, no doubt, to the longitudinal dikes of the tunnels, but they do not exhibit any marked foliation, agreeing in this respect with the enclosing diorite and granite. They are, however, much faulted and exhibit a good degree of discontinuity. No dikes of the north-south series were observed in this area. Between the dam and tunnel Number 5 the excavation for the aqueduct, confirming the natural ledges, showed alternating normal and fine granite, chiefly the former, with some diorite.

Tunnel Number 5.

This tunnel is 600 feet long, extending from Station 665 + 00 to 671 + 00, all in rock, and the open cut at the east end extends the continuous rock section to fully 850 feet. The formation is practically all diorite, similar to that in the western part of tunnel Number 4, with numerous irregular dikes and masses of fine granite and occasional narrow veins of pegmatite.

Both the fine granite and the pegmatite are of a bright pink or reddish color, and the pegmatite veins, with abundant red feldspar, grade into veins of nearly pure vitreous quartz. The diorite exhibits the usual gradation in texture from nearly compact to a moderately coarse granitic structure, and it is much jointed and slickensided. Several well-marked shear zones or possible faults were observed, and one of these, 4 to 6 inches wide, crosses the tunnel at the east portal nearly at right angles, with an easterly hade of about 45 degrees.

Although the conditions were exceptionally good for a thorough examination, only one trap dike was observed, and this is of doubtful character, being possibly a highly oxidized, ferruginous, and decomposed, dike-like zone of the diorite. It is 2 to 3 feet wide, and crosses the cut east of the tunnel at Station $672+05$.

Between tunnel Number 5 and the terminal chamber of the aqueduct, a distance of 3,600 feet around the south side of Doublet Hill, the ledges are numerous and, together with the excavation, afford a nearly continuous section; and nowhere perhaps on the entire line of the aqueduct does it traverse a more typical complex of the granitic rocks. The diorite prevails, especially near the tunnel and again for the last thousand feet or so before reaching the terminal chamber, while the middle part of the section is chiefly normal granite with some fine granite, and the terminal station itself rests upon the normal granite. The main point, however, is the frequent alternations and wholly irregular relations of these rocks, the diorite even where most continuous being divided by dikelets and masses of both normal and fine granite, and the granite in turn enclosing and injecting the diorite. Several dikes of greenstone diabase with a general east-west trend were observed. These are of similar character to those observed in the basin of the reservoir, and, as there, no dikes of the north-south series were noted. This is not surprising, however, so far as the natural ledges are concerned, since the ready and deep decomposition of the north-south dikes makes them little likely to outcrop.

Age and General Relations of the Rocks.

The only definite clue to the stratigraphic position or geologic age of these rocks appears to be that afforded by the metamorphic sediments, which are clearly and well developed only in the vicinity of the Sudbury Dam and in tunnel Number 4. Their extreme alteration

has long since obliterated the last vestige of paleontological evidence, if such ever existed; and the only grounds for legitimate inference appear to be lithologic character and relations to the granitic series, assuming the general contemporaneousness or geologic equivalence of the plutonic rocks throughout this section and the Boston Basin district. The sediments are clearly older than any of the igneous rocks with which they are associated, and the latter are, doubtless, at least as old as the corresponding rocks of the Blue Hills and Weymouth, which intersect strata of proved Cambrian age and are overlain by Carboniferous sediments. That the sedimentary rocks on the line of the Weston Aqueduct in Southboro and Weston are either Cambrian or older would probably be questioned by none. The strong probability that the plutonic rocks of the Boston Basin region, if not of all eastern Massachusetts, represent but varying phases of one and the same great batholith developed during the Cambrian-Carboniferous interval, and the complete absence in the Blue Hills complex of any trace of the floor on which the known Cambrian sediments were deposited, the pre-Cambrian terranes, together with large volumes of the Cambrian strata, having been absorbed in the development of the batholith, seem to leave no reason to doubt the Cambrian age of all of the pre-granitic strata; or at least that may be accepted as the most probable provisional hypothesis. The quartzites and slates on the line of the Weston Aqueduct, it is well known, are continued to the northeastward, with similar plutonic associations, through Lincoln, Waltham, Lexington, Arlington, Woburn, Stoneham, and other towns to the Merrimac and the sea, and southwestward through Natick and Sherborn, and possibly farther. Throughout this belt the sediments are chiefly quartzites grading into flinty slates and hornstones, which may be more or less micaceous, but including to the northeastward in Stoneham and other towns, as also on the peninsula of Nahant, calcareous beds; and that these isolated masses of sediments, representing a once continuous sedimentary cover of the batholith, are best referred provisionally to the Cambrian is, I believe, the general consensus of opinion among students acquainted with the facts, more especially since the Cambrian age has been definitely determined at several points, including Nahant, by the finding of characteristic fossils by Sears and others.[1] A glance at the distribution of the sedi-

[1] Bulletin Essex Institute, **22**, 1–17; **23**, 1–16.

ments, essentially as islands in a sea of plutonic rocks, together with their metamorphic character, leaves no room to doubt that the contacts are everywhere igneous, as, in fact, the structural details clearly show.

The intimate association of the diorite with the metamorphic sediments in tunnel Number 4, as throughout the Cambrian belt of Middlesex and Essex Counties, suggests for it, as previously noted, a peripheral position in the batholith; and in view of the fact that in its relations to the granite it is seen always to be the older rock, although often clearly related to the granite in composition, we need not doubt that it is an earlier crystallization of the same magma and a product of magmatic differentiation, nor that it formed originally a more or less continuous contact zone between the main granite body of the batholith and its cover of Cambrian sediments. That the principal bodies of fine granite with blending contacts hold a somewhat similar relation to the normal granite, a product chiefly, however, of textural rather than of chemical differentiation, is obvious, while the sharply defined dikes of fine granite and microgranite as clearly represent later intrusions of still unsolidified magma.

The fact that the true gneissic structure of the normal granite is developed only locally, and for the most part, at least, marginally or near a contact with the sedimentary rock or diorite, suggests its origin as a primary flow structure, as has been urged in the case of the great dike of granite porphyry with gneissic borders in the vicinity of Clinton, Massachusetts.[1] The effects of dynamic metamorphism are, however, very manifest in extensive semicrushing and frequent shear planes and zones, which are more marked in the western than in the eastern part of the field, and have to a great extent impaired the strength and solidity of the granite. Aside from the original and secondary structure planes, the granites are of uniform character throughout the field, or at least there are no contrasts that would suggest diversity of age or origin. On the contrary, the facts all appear to be consistent with the view that under a common cover of siliceous and argillaceous strata, a magma, resulting in large part from the fusion and absorption of these sediments, has yielded by the processes of magmatic differentiation (chemical and textural) the various members of the granitic series, including the normal granite, forming the main body of the batholith, the diorite and fine granite of the contact zone, and the later intrusions of fine granite. Although assumed to have been formed *in situ*

[1] Technology Quarterly, 12, 95–96.

by a progressive, upward refusion of a previously solidified portion of the terrestrial crust, subsequent movement of the actually or potentially liquid magma sufficient to render it locally intrusive is indicated by the marginal gneissic structures and by the innumerable dikes and dikelets of granite in the diorite, and of both granite and diorite in the covering sedimentary rocks.

One of the most interesting generalizations in the geology of the Boston Basin, first clearly worked out in the South Shore districts,[1] is that the post-granitic, basic, or diabase dikes belong to two series distinct in character, trend, and age — an older series of approximately east-west, greenstone or highly chloritized dikes, and a younger series of north-south, relatively non-chloritized dikes, which are farther characterized by a prevalent columnar structure and ready kaolinization. In no part of the Boston Basin region, apparently, are these two series more strongly contrasted in composition, structure, or age than on the line of the Weston Aqueduct. The contrast increases westward, and is largely due to the fact that the older, east-west series, antedating the crushing and shearing of the granitic rocks, has shared in the dynamic metamorphism of the latter, developing a marked schistosity and such a preponderance of biotite in the composition as has seemed to prove a bar to the general chloritization of the ferro-magnesian constituents noted farther eastward.

The best conclusion in regard to the chronology of the basic dikes seems to be that the older, metamorphic series, as well as the dynamic metamorphism of the granitic rocks, dates from the Appalachian Revolution, or the folding and faulting of the Carboniferous sediments (conglomerate and newer slate) of the Boston Basin; and in this connection it is interesting to note at least a general agreement in trend and hade of these dikes and the axial planes of the Carboniferous plications. In the north-south dikes, on the other hand, we note features of trend, structure, and composition which ally them with the Triassic dikes of the Atlantic seaboard, which, it is well known, are by no means confined to the areas of Triassic sedimentation, and represent a period when the crust, stiffened by the Appalachian plications, suffered further deformation by faulting rather than by folding.

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[1] Occasional Papers Boston Society Natural History, 4, 107, 258, 513.

PETROGRAPHICAL NOTES ON THE ROCKS OF THE WESTON AQUEDUCT.

By C. H. WARREN.

The following notes are designed to present the results of a microscopical study of some of the igneous rocks met with in the tunnels of the Weston Aqueduct. The macroscopic characters and structural relations are fully discussed in the preceding pages by Professor Crosby, so that what follows is supplementary to his paper.

Dikes of the East and West Series. — Thin sections from dikes of the east and west series show that, so far at least as mineralogical composition is concerned, there are two distinct rocks. One of these is characterized by an abundance of hornblende, and may be designated for convenience as a hornblende rock. In the other, biotite is the most important constituent, and the rock may be termed a biotite schist.

Of the first type, sections have been examined from dikes near Stations Numbers $42+20$ and $72+00$. Sections from $42+20$ show the rock to consist of a confused, fine-grained aggregate of hornblende, epidote, feldspar, and quartz, with a subordinate amount of biotite and chlorite. Of these, the first two comprise somewhat more than half of the rock.

The hornblende belongs to the green, uralitic variety, and is the most abundant and conspicuous mineral present. It lacks entirely any crystallographic boundaries of its own, although an occasional one of the larger individuals preserves rather indistinct outlines of an original augite phenocryst. Much of the hornblende is scattered through the rock in the form of small shreds and flakes. Besides having the characteristic reedy appearance, much of it is bent and twisted. With low magnifying powers a flow structure can be seen, which is due to a tendency toward a parallel arrangement of the hornblende. The pleochrism is strongly marked as follows: A, pale yellowish green to nearly colorless; B, green; C, greenish blue. The absorption is $A>C>B$. The maximum extinction measured was 23° on c'. It may be remarked

that the blue pleochrism is unusually strong, and that the absorption does not follow the usual order for common hornblende.

The hornblende has suffered considerable alteration to chlorite, which occupies the position of the original mineral and closely resembles it, being, however, readily distinguished by the very low polarization tints.

Epidote is very abundant. It occurs in well-marked, rounded crystals, rarely exceeding 0.3 millimeter in diameter, and ranges from this to extremely minute grains. It is also commonly seen in very fine granular aggregates. The epidote is nearly colorless, the larger grains showing a slight yellowish pleochrism.

Although the feldspar of the rock occurs in very irregular individuals with indistinct boundaries, the general habit is that of crystals tabular on M (010). The mineral has suffered severely from crushing and metamorphism. Traces of carlsbad and albite twinning can be seen, but the extinctions are undulatory and too uncertain to permit of an exact determination. The measurements made, however, point to a moderately basic labradorite. The comparatively large size of some of the feldspars indicates that the mineral was to some extent porphyritic. The crystals are crowded with minute crystal inclusions, some of which are epidote, others appear to be albite, while more, which are possibly sillimanite, could not be determined. Calcite and kaolin were not noticed.

Quartz is abundant and is evidently of secondary origin. It is intimately associated with the feldspar in the form of small grains, which are often crowded with minute inclusions. The light-colored areas of the section consist of a confused mixture of feldspar, quartz, shreds of hornblende, chlorite, and grains of epidote.

The biotite is of the ordinary brown variety, and appears in the form of irregular shreds intimately associated with the hornblende.

Sections from the dike near Station $71+00$ bear some strong points of resemblance to the preceding. It differs from it, however, in containing a much greater proportion of hornblende and biotite, in rarely showing large grains of epidote, and in the almost total lack of feldspar. The hornblende and biotite have the same general appearance as described under $42+20$, although there is a more pronounced tendency toward a uniform orientation and segregation into streams or roughly outlined bands. The epidote appears much more commonly in finely granular aggregates scattered through the rock. The epidote

with quartz, shreds of hornblende, biotite, chlorite, and an occasional feldspar grain constitute a very fine-grained, confused mosaic, more or less continuous in indistinctly outlined streams, which conform roughly to the direction of flow indicated by the hornblende.

The dike at 71 + 00 shows the greater degree of metamorphism. In the small amount of feldspar, greater amount of biotite, and its general structure it shows some points of resemblance to certain of the rocks described beyond in which hornblende is absent.

Of the second type, viz., that in which biotite is prominent, sections have been studied from dikes met at or near Stations 47 + 00, 68 + 00, 114 + 35, and 130 + 50.

Section from 47 + 00. — This rock is a fine-grained mixture of biotite, plagioclase feldspar, and epidote with some quartz. The feldspar constitutes roughly one-half of the rock, and occurs in individuals of a fairly uniform size, frequently lath-shaped, more often equidimensional, and always with very indistinct boundaries. They contain many minute crystalline inclusions, some of which could be identified as biotite and epidote. Other quite numerous inclusions have the appearance of fibres or slender rods. They show low polarization tints, an inclined extinction, but further than this little could be ascertained regarding them.

The mica is a greenish brown variety with a strong absorption, and belongs among the iron-rich biotites. It occurs in the form of small flakes, and, next to the feldspar, is the most important constituent. The biotite and the epidote, which latter is abundant in the form of small grains and granular aggregates, are chiefly confined in their distribution to the spaces between the feldspars where quartz also occurs. This at once suggests that these minerals occupy the position of original augite, which by its alteration gave rise to the biotite with the separation of epidote and quartz.

Dike at 68 + 00. — This rock consists of biotite, epidote, and a subordinate amount of quartz. Feldspar was almost entirely absent from the slides examined. The biotite is of the same variety as described above, and makes up, probably, three-quarters of the rock. It is intimately mixed with epidote grains so that the slide has the appearance of being composed of biotite and epidote with a background of quartz. The schistose structure is very evident.

Dike at 114 + 35. — This rock, like the preceding, is composed essentially of biotite, epidote, and quartz. The biotite and epidote

occupy, however, a larger proportion of the specimen. Besides scattered grains the quartz is seen in narrow veins with epidote and some calcite. There are also occasional areas, sometimes having a diameter of 3 or 4 millimeters, which are composed almost entirely of quartz grains. All of the quartz shows a cloudy and broken extinction. The biotite has suffered some alteration to chlorite. An occasional shred of muscovite occurs, and pyrite grains are also present.

Dike at 130 + 50. — This rock has undergone even more severe crushing than any of the others which have been studied, and has also suffered more from superficial weathering. The minerals, which can be distinctly seen under low powers of the microscope, are biotite, calcite, and epidote. The biotite occurs in scattered blotches throughout the section, the calcite in well-marked, relatively large grains, often showing the cleavage very perfectly. Epidote is apparently less abundant than in the other rocks. The greater part of the rock consists of finely comminuted material, which under high magnifying powers resolves itself into a mass of quartz grains and biotite with some epidote. The biotite has, to a large extent, been bleached, a process which is accompanied by a lowering of the double refraction.

Remarks on the East and West Series of Dikes. — The field relations of these dikes taken in connection with their mineral composition can hardly point to any but a diabase for the original rock, and, although in the absence of chemical data it cannot be proved that they have all resulted from the metamorphism of dikes identical in chemical composition, it appears highly probable that such is the case. Their present mineralogical differences represent then, it is believed, the various effects of severe, deep-seated metamorphism acting on a series of diabase dikes, varying only as regards size and granularity. The original constituents, chiefly plagioclase and augite, gave rise in some cases to hornblende with more or less biotite, in others to biotite without hornblende, epidote and quartz always accompanying. The two dikes in which hornblende occur show, in general, rather less evidence of crushing and shearing than those of the biotitic type. In the dike near Station 71 + 00 the metamorphism has apparently been more severe than in the one near 42 + 20; and in the former considerable biotite is present and little or no feldspar. In the biotitic types hornblende is absent; and the feldspar is also lacking in those dikes which show evidences of the most severe crushing and shearing. These facts seem to indicate that the biotite-epidote

schist is the more highly metamorphic of the two types. It should be noted that all the sections examined, with the exception of those from Number 114 + 35, are free from calcite and kaolin or other effects of superficial weathering.

Dikes of the North and South Series. — Sections from these dikes present a striking contrast to those of the east and west series. All the sections examined show that these dikes are a highly typical, porphyritic diabase, and that they vary among themselves only in the relative granularity of their crystallization and in the extent to which superficial weathering has progressed. Feldspar and augite are developed porphyritically and appear to be contemporaneous in age. Olivine was originally present in porphyritic crystals, but is now wholly altered. The feldspars have a fine lath-shaped development, sometimes attaining a length of 5.0 millimeters. They are beautifully twinned after the carlsbad, albite, and pericline laws. Zonal development is common. The extinction angles, measured after the method of Michel Lévy, show that the feldspars range in composition between basic andesine and basic labradorite. The interior of the feldspars often shows decomposition to zeolitic aggregates. Sections from more highly weathered dikes show the feldspars largely or wholly changed to zeolites, calcite, quartz, and kaolin.

The augite phenocrysts are much less abundant than the feldspars. They are beautifully fresh and in the coarser grained dikes attain a considerable size. Olivine was about as common as the augite, usually in large crystals, but has suffered complete decomposition to a confused mixture of serpentine, carbonates, and quartz, with a separation of magnetite chiefly about the borders. In some of the finer grained rocks olivine does not appear to have developed porphyritically, although it may have been originally present in the ground mass.

Between the phenocrysts and the ground mass there is a decided break in the time of crystallization. The feldspars of the ground mass have the same composition as the porphyritic crystals, follow the same twinning laws, but show, in general, less weathering. They occupy approximately one-half of the area of the section.

Besides the augite, the spaces between the feldspars are often filled with a yellowish green, decomposition product, having a serpentine-like appearance. This may result from the alteration of olivine, but is more likely mesotasis. No olivine now exists in the ground mass. If it were there, it was in subordinate amount. Magnetite is abundantly

scattered through the rock as an original mineral, aside from that resulting from the alteration of the olivine and augite.

The weathering process is indicated by a decomposition of the feldspars as already described, and by the appearance of chlorite and other products in the ground mass, causing this to turn green and darken. The augite phenocrysts show also an alteration to chlorite with the separation of magnetite.

The sections from these dikes present, when compared with those from the east and west dikes, quite as striking differences as the rocks themselves do in the field, and leave no doubt that they belong to a distinctly different generation.

The Diorite. — Thin sections of the diorite were examined from various points between Stations 534+00 and 562+50. The rock appears throughout to be a fairly normal diorite, moderately coarse-grained, showing, however, some variation as to grain and in the relative amounts of the various constituents present.

The hornblende is the common green variety, sometimes very light in color, and in most of the sections shows considerable alteration to chlorite, epidote, and quartz. It is always abundant, sometimes being present in very large amount. It rarely shows any crystallographic boundaries. Biotite is generally present in small amount and often shows a fine development of rutile needles between the leaves.

The feldspar is more or less automorphic, with a strong tendency toward the lath-shaped structure. In fact, the resemblance to the diabase structure is sometimes very strong, notably in sections from the diorite at Stations 534+00 and 559+50. In these sections the position of the hornblende between the feldspars is exactly similar to that of the augite in the diabases, suggesting at once that the hornblende is uralitic, and that the rock is at times more diabasic than dioritic in character. The feldspar is practically all labradorite. Carlsbad and albite twins are common. Practically all of the feldspar shows considerable alteration.

Epidote is very prominent, being present practically everywhere. Considerable areas of the sections are at times composed entirely of granular masses of epidote, mixed with quartz and chlorite, which have replaced the original constituents. In the more highly altered types kaolin and calcite appear. Veins of epidote and quartz are also common.

Quartz is present in all the sections as an original mineral occupying the small spaces between the feldspar crystals.

Magnetite is always present and is often thickly distributed throughout the rock. Ilmenite, with its characteristic peripheral alteration to leucoxene, is often seen in fairly large individuals. Apatite is common in the form of small crystals and occasionally attains considerable size. Pyrite was present in many of the sections examined.

Fine Granite. — Two sections of the fine-grained phase of the granite were examined from dikelike intrusions near Stations 567 + 00 and 672 + 00.

Sections from the intrusions at 567 + 00 exhibit a typical microgranitic texture. The feldspars are largely othoclase with a considerable amount of plagioclase (oligoclase and albite) present. All of the feldspars are slightly dusty in appearance and show numerous bright specks of secondary minerals. Quartz is abundant and uniformly exhibits a cloudy and broken extinction. Dark-colored constituents are practically absent, only a few flakes of hornblende, largely changed to chlorite, being present. Epidote is common in the form of minute grains, which are distributed along lines of finely crushed material, forming veins.

The rock from near Station 672 + 00 is aplitic in character. The feldspars, which are albite and oligoclase with a subordinate amount of orthoclase, are much more abundant than the quartz, which is largely confined to the spaces between the feldspars and is the least automorphic of these minerals. Magnetite grains are scattered sparingly through the section. Epidote is rare; occasionally calcite is seen, while a few shreds of hornblende, chlorite, and muscovite are present.

A few large phenocrysts of acid plagioclase indicate a tendency toward a porphyritic habit in the rock.

BOOK REVIEWS.

Proceedings of the Chemical and Metallurgical Society of South Africa.[1]

Everybody interested in the cyanide process for treating gold ores will welcome the second volume[2] of the Proceedings of the Chemical and Metallurgical Society of South Africa, the members of this society having excelled in the development of that branch of metallurgy. The book contains the papers and discussions of the thirty-five meetings held between 1897 and 1899. Their importance can be judged by the fact that most of them have been reprinted in full or in part by the leading periodicals as soon as issued in pamphlet form. The metallurgist interested in cyaniding will be glad to have these scattered papers brought together in a single handy volume. The discussions, as a rule not given in the reprints and therefore new to most readers, are of much value, especially as they come from men working in the field and the laboratory along the same lines as the authors of the papers. Their characteristics are avoiding of generalities and going direct to the point. The titles of some of the papers are: "Precipitation of Gold from Cyanide Solutions" (Ehrmann); "The Reduction of Zinc-gold Slimes" (Johnson); "The Treatment of Battery Slimes" (Williams); "The Solution of Gold in Accumulated and Other Slimes" (Caldecott); "The Stamp Milling of Gold Ores in its Relation to Cyaniding" (Johnson); "Discrepancies in Slime Treatment" (Caldecott); "The Estimation of Oxygen in Working Cyanide Solutions" (Crosse); "A Continuous Process for Slime Treatment" (Rand), etc.

Although the main part of the volume is devoted to cyaniding, it is not confined wholly to this process; mining and metallurgy of other non-ferrous metals are represented. The book closes with 125 pages of appendices having the following headings: Interim Report of the Assay Differences Committee; Contributions and Correspondence; Obituaries; Notes and Comments; Notices and Abstracts, Patent. The index shows that much care has been given to its preparation. The volume is a valuable addition to the literature on the cyanide process, which is already very large.

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[1] Proceedings of the Chemical and Metallurgical Society of South Africa, Vol. II, February, 1897, to September, 1899; Johannesburg (Edinburgh, R. W. Hunter; New York, *Engineering and Mining Journal*), 1903, xx + 928 pages, illustrated. Price, New York, $6.00.

[2] Volume I was issued in 1897.